INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS - Irish Group

DEVELOPMENTS in IRISH Hydrogeology IN A CHANGING WATER Services & Planning ENVIRONMENT

Proceedings of the 37th Annual Groundwater Conference
Tullamore, Co. Offaly, Ireland

25th and 26th April 2017

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

"Developments in Irish Hydrogeology in a Changing Water Services and Planning Environment'

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Tullamore Court Hotel
Tullamore
Co. Offaly

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INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP)

Introduction

Founded in January 1976, the IAH (Irish Group) has grown to more than 130 members at present. The IAH (Irish Group) is represented by a wide range of professionals working in academia, public bodies, State agencies, and consultancies. The activities of the IAH (Irish Group) are organized and led by a volunteer committee of members, comprising a President, Secretary, Treasurer, Burdon Secretary, Northern Region Secretary, Fieldtrip Secretary, Education & Publicity Secretary, as well as a Conference Secretary who is supported by a conference sub-committee.

The IAH (Irish Group) hosts a range of events every year, mainly to bring professionals together but also to raise awareness about hydrogeology to a wider audience. Regular activities of the Irish Group consist of the annual 2-day conference (traditionally held in Tullamore), an annual weekend field trip, and a series of 'technical discussion meetings' (lectures) that reflect ongoing research or projects of general interest to the Irish hydrogeological community. The lecture series incorporates the Annual Burdon Lecture on groundwater issues in the developing world, often with invited speakers from abroad.

Other activities of the IAH (Irish Group) include submissions to the Irish Government or public bodies on groundwater, the environment, and matters of concern to members; Organising the cataloguing of the Burdon library and papers, which are now housed in the Geological Survey of Ireland Library; and contributing to the Groundwater Newsletter published by the Geological Survey.
The IAH (Irish Group) is a sponsoring body of the Institute of Geologists of Ireland (IGI). We also provide small bursaries to post-graduate students pursuing degrees which have an emphasis on hydrogeology. We further sponsor annual subscriptions of select members in other countries as part of the Sponsored Membership Scheme of the IAH. If you would like to apply for a student bursary, details can be found on the IAH (Irish Group) website shown below.

The IAH encourages members to highlight their local IAH chapter to their colleagues/ students, and to invite anyone they feel may be interested to join.

For more information please refer to:	www.iah-ireland.org
Future events:	www.iah-ireland.org/upcoming-events/
IAH Membership (new or renewal):	www.iah.org/join_iah.asp
	www.iah.org/payonline

Funding for IAH (Irish Group) activities is derived from membership fees and the annual conference. We welcome the participation of non-members in all our activities. The student bursary scheme is funded by annual contributions from Irish hydrogeologists and hydrogeology and environmental consultancies.

2017 IAH (Irish Group) Conference

The theme of this year's conference is *Developments in Irish Hydrogeology in a Changing Water Services and Planning Environment.* The aim of the conference is to highlight topics that are shaping and otherwise influencing the hydrogeological profession at the present time, and to engage with the technical and scientific challenges that are emerging from a changing water services environment. The objective is to deliver a conference that informs about *where* the main pressure points of water resources management lie and *how* hydrogeologists contribute towards problem-solving.

In the past few years, a somewhat clouded picture of water supply and water resources management has emerged. On one hand, there is a trend towards consolidation of water supplies, where water quality is managed at source by means of (often expensive) treatment technologies. On the other hand, a significant catchment management initiative is underway, where source and drinking water protected areas play a long-term management role, where water quality issues are addressed at the larger catchment scale.

Both approaches are concerned with water quality improvement. However, while both approaches are compliance-focused, they also reflect very different objectives, in response to different directives and regulations.

Importantly, both approaches provide space for the hydrogeological profession, and both require inputs from the hydrogeological profession. Hydrogeology is undeniably a unique science in that it truly links the site-specific factors that determine risks of impact through the source-pathway-receptor model of environmental risk assessment.

There is an unawareness by many, and perhaps a tendency by others, to forget or ignore that hydrogeology, more than anything else, influences water quality at individual sources, whether they be groundwater or surface water-based. Therein lies our challenge. The applied skills and experiences of our profession can play an important role both in assessing the problem and framing the solution. In a water supply context, some sources simply do not require expensive treatment. However, in other cases, they do. Looking up into the wider catchment or contributing area of a source informs about needs and cost-effectiveness of measures, and benefits both the suppliers and regulators.

The IAH (Irish Group) is tasked with engaging stakeholders on such matters. Linking hydrogeology to water resources management and source water quality is part of that engagement. Over the two days of the conference, we will hear presentations from national and international speakers representing academia, local authorities, national agencies and consultancies. We will also converse during social settings, and share perspectives on the topics related to the conference theme.

We are particularly pleased to welcome Irish Water, Environmental Protection Agency (EPA), Geological Survey of Ireland, local authorities and group water scheme representatives to the conference, both as contributors and participants. We are also thrilled to welcome our keynote speakers - Donal Daly, Mike Packman and Dr. Attila Kovács.

Donal Daly is a Senior Scientific Officer with the Irish EPA, currently leading their Catchment Science & Management Unit. Donal will share his perspectives on this year's conference theme, and is uniquely qualified to do so in his singular role as one of Ireland's leading hydrogeologists during the past 30 years. Few individuals have had a greater influence on the Irish hydrogeological profession than he.

Mike Packman is Chief Hydrogeologist with the Southern Water Group in the UK, where he manages the water resources sustainability programme, oversees water source production planning, and leads their asset management planning. Mike will share his 40+ years of professional experience working in one of the largest water utilities in the UK, addressing the wide scope and significance of hydrogeology in the planning, monitoring and protection of groundwater resources in a water utility context.

The presentations by Donal and Mike will set the stage for the first day of the conference, linking the sessions on groundwater resource planning and groundwater hazards and pathways, which includes newly published research findings on contaminant transport to rivers via diffuse and preferential groundwater pathways.

Dr. Attila Kovács of the Geological and Geophysical Institute of Hungary will share his research findings on the reactivation of a regional karst system in Hungary as a result of rising water levels, posing major challenges and risks to existing infrastructure. His presentation provides the introduction for the second day of the conference, which segways into a conference session on geo-risks associated with karst systems, which includes an update on research of geo-risks, including groundwater flooding in Ireland, innovative and publically available methods to detect ground-motion (in a groundwater context), and the geological context of natural arsenic concentrations in groundwater. We will also receive updates on the significant body of work that has been carried out in the last 2 years relating to trihalomethanes in water supplies, their origins, with a case study of how hydrogeology influenced decisions to change the source of a public water supply.

We are also happy to continue the popular tradition of the *Early Career Hydrogeologists Network (ECHN),* which is accompanied by a presentation of the winner of the competition for the best hydrogeological Conceptual Site Model. The competition, which was initiated by Gerry Baker in conjunction with the IAH (Irish Group), runs for the first time this year, and will hopefully become a standard contribution to the conference in the coming years.

The first day of the conference will be followed by a wine reception, kindly sponsored by *City Analysts*, as well as the subsequent social evening at Hugh Lynch's Bar.

The annual conference will be rounded off on the second day with a technical workshop, hosted and led by the EPA and the Office of Public Works on the topic of telemetry and telemetric data transmission. This is a great opportunity to learn about a topic which is becoming ever-more routine in hydrological and hydrogeological monitoring and management practice.

Lastly, we wish to take this opportunity to welcome all participants to the conference and trust that the programme will be 'eventful' and rewarding for all.

With best regards, and looking forward to seeing you at the conference,

Philip Schuler, Conference Secretary, IAH (Irish Group)
Henning Moe, President, IAH (Irish Group)

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For more information and contact details please refer to: *www.iah-ireland.org*

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The proceedings for the 37th Annual Groundwater Conference 2017 will also be made available digitally on the IAH-Irish Group website within the next six months.

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The IAH (Irish Group) would also like to acknowledge the support of the following members and organisations whose staff have worked on the committee of the IAH-Irish Group throughout the year and helped to organise the conference:

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‘Developments in Irish Hydrogeology in a Changing Water Services and Planning Environment’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tuesday 25th & Wednesday 26th April 2017

Programme Day 1, Tuesday 25th April

08:30 - 09:30 *Conference Registration; Tea, Coffee, & Exhibits*

INTRODUCTION

09:30 – 09:40 Welcome and Introduction
Henning Moe – *President IAH Irish Group*

SESSION 1: KEYNOTE

09:40 – 10:10 ‘Change Thoughts, Change Destiny’ – Donal Daly (Environmental Protection Agency)

10:10 – 10:40 ‘Sustainable groundwater resource planning and management’ – Mike Packman (Southern Water)

10:40 – 10:55 Q & A

10:55 – 11:20 *Refreshments*

SESSION 2: TOWARDS SAFE AND EFFECTIVE GROUNDWATER SUPPLY

11:20 – 11:40 ‘National Water Resources Plan’ – Angela Ryan (Irish Water)

11:40 – 12:00 ‘Know your ZOCs from your SPAs – Groundwater Source Protection terminology and usage’ – Taly Hunter-Williams (Geological Survey of Ireland)

12:00 – 12:20 ‘Water Quality – “Prevention or Cure” a Local Authority perspective’ – Michael O’Hora (Laois County Council)

12:20 – 12:40 ‘Towards energy-efficient water wells through optimization of well hydraulics’ – Georg Houben (Federal Institute for Geosciences and Natural Resources)

12:40 – 13:00 Q & A

13:00 – 14:00 *Buffet lunch in Tullamore Court Hotel*

SESSION 3: GROUNDWATER HAZARDS AND PATHWAYS

14:00 – 14:20 ‘Understanding pathways transferring nutrients to streams – implications for water quality management strategies’ – Jenny Deakin (Environmental Protection Agency)

14:20 – 14:40 ‘What are the main sources of nutrient inputs to Ireland’s aquatic environment? Results from the SLAM framework’ – Eva Mockler (University College Dublin)

14:40 – 15:00 ‘The influence of hydrogeological setting on nitrate fate and transport in Irish and British aquifers and the implications for catchment management’ – Alison Orr (ARUP)

15:00 – 15:25 *Refreshments*

15:25 – 15:45 ‘The application of quantitative trace techniques to assess diffuse metal contamination from the former Avoca mine site’ – Patrick Barrett (CDM Smith)

15:45 – 16:05 ‘Implementing guidance on the authorisation of discharges to groundwater – experience from one Local Authority’ – Emmet Conboy (Meath County Council)

16:05 – 16:20 Q & A

SESSION 4: EARLY CAREER HYDROGEOLOGISTS NETWORK

16:20 – 16:35 ‘Socio-hydrogeology: bridging the gap between science and society to better address aquifer contamination’ – Viviana Re (University of Pavia)

16:35 – 16:50 ‘Development of a focused Integrated Catchment Management toolkit for use in secondary schools’ – Grainne Barron (National University of Ireland Galway)

16:50 – 17:05 ‘A sensitivity analysis in relation to climate change impacts on groundwater recharge to Irish Fractured-bedrock aquifers’ – Elia Cantoni (Trinity College Dublin/ ICRAG)

17:05 – 17:20 ‘Dye tracing groundwater in the Rathcroghan Uplands, Co. Roscommon’ – Natalie Duncan (Independent Geoscientist)

17:20 – 17:35 Q & A

17:35 *Poster Presentations & Wine Reception*

18:30 *Social event at Hugh Lynch’s Bar including a light evening meal, sponsored by IAH (Irish Group).*

Programme Day 2, Wednesday 26th April

08:30 – 09:00 *Tea, Coffee & Exhibits*

SESSION 5: KEYNOTE

09:00 – 09:30 ‘Reactivation of karst springs after regional mine dewatering in the Tata area, Hungary’ – Attila Kovács (Geological and Geophysical Institute of Hungary)

09:30 – 09:45 Q & A

SESSION 6: GEO-RISKS RELATED TO GROUNDWATER

09:45 – 10:05 ‘Monitoring, mapping and modelling groundwater floods in Ireland’ – Owen Naughton (Geological Survey of Ireland)

10:05 – 10:25 ‘How understanding hydrogeology can reduce risks on large linear infrastructure projects’ – Catherine Buckley (ARUP)

10:25 – 10:45 ‘Space-borne interferometric synthetic aperture radar (InSAR) for detecting geo-risks relate to hydrogeology’ – Alessandro Novellino (British Geological Survey)

10:45 – 11:05 ‘Arsenic contamination of drinking water in Ireland: A spatial analysis of occurrence and potential risk’ – Ellen McGrory (National University of Ireland Galway)

11:05 – 11:20 Q & A

11:20 – 11:45 *Refreshments*

SESSION 7: DOC & THM

11:45 – 12:05 ‘Drinking water supply sources & dissolved organic carbon: Irish groundwater versus surface water’ – Pamela Bartley (Hydro-G)

12:05 – 12:25 ‘Identifying sources of natural organic matter (NOM) and trihalomethanes (THMs): Case study from a groundwater spring in a karst region in the west of Ireland’ – Connie O’Driscoll (Ryan Hanley)

12:25 – 12:45 ‘The Dingle Toe: strategic use of groundwater to reduce water treatment efforts, while improving well installations at the same time’ – Malcolm Doak (Irish Water)

12:45 – 13:05 ‘Groundwater dissolved organic carbon (DOC) and human health risk: Some issues to consider’ – Shane Regan (Trinity College Dublin)

13:05 – 13:20 Q & A

13:20 Conference closing address: Philip Schuler (*Conference Secretary* – IAH Irish Group)

13:30 *Buffet lunch in Tullamore Court Hotel*

TECHNICAL WORKSHOP

14:30 Telemetric data transmission – Kenneth Freehill and William Delaney (OPW), Rebecca Quinn (EPA)

16:00 End of Workshop

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SESSION 7: DOC & THM

SESSION I

"CHANGE THOUGHTS, CHANGE DESTINY"

Donal Daly
Environmental Protection Agency

ABSTRACT

We live and work in a world in which the environment is challenged by the activities of humankind. The natural capital on which life on the planet depends is deteriorating. While the overall quality of Ireland's environment is good in comparison to many other countries, the situation with our water quality, biodiversity and greenhouse gas emissions is unsatisfactory. As the future is everyone's responsibility, there is an onus on us to evaluate how we, both as individuals and groups, can contribute to the changes that Irish society needs to make. This paper presents thoughts on ways that we can do this by: i) putting people at the core of environmental management; ii) ensuring genuine sustainable development by developing and utilising the natural capital approach; iii) integrating geosystem services into natural capital as a parallel service to ecosystem services thereby making it more holistic and defensible as an approach; iv) making Integrated Catchment Management (ICM) the over-arching framework and process for water management; v) understanding and promoting the role of hydrogeologists in the context of connecting with other disciplines, being objective in the advice given and looking outside that area of expertise and responsibility; and vi) setting out to be translators of hydrogeological expertise and knowledge to policy makers and the public, and in the process provide translational leadership. There are reasons to be positive, but only if we work to change the current disimproving environmental trajectory.

INTRODUCTION

The thinking behind this paper is based on the view that, while we as hydrogeologists, catchment scientists, geoscientists, water scientists or water engineers (these are often overlapping) have to focus on the detail of our area of responsibility, by 'looking up' from this area and our discipline:

- we can have a greater impact as 'citizens of the world' in managing the earth's and Ireland's natural capital in a sustainable manner, including our water resources and biodiversity; and
- we can get personal satisfaction and benefit.

However, this can be challenging both for individuals (such as this author) and organisations, who may be over-influenced by specialist or sectoral perspectives thereby hindering or at least not contributing to the achievement of the broader objectives required for a sustainable future. The phrase "*change thoughts, change destiny*"[1] reflects a lesson learned late in a working life as a geoscientist on the benefit of 'looking up from the borehole' and realising the need and benefit of also taking a broad perspective of our personal and organisational roles and responsibilities. The purpose of this paper is not to try to give answers and prescriptions but to raise issues and questions to encourage THOUGHTS which lead to WORDS which lead to ACTIONS which lead to HABITS which lead to DESTINY. Each reader can decide what that 'destiny' should or could be. If the conclusion is that changes are needed, the request is '*be the change that you wish to see in the world*'[2]. The reality is that geoscientists can and must play a major role in ensuring a genuinely sustainable future.

[1] Phrase used by Paudie Butler, GAA coach.

[2] Quote attributed to Mahatma Gandhi.

In making the points raised in this paper, it is recognised that some or even many may not be agreed with. However, the purpose is to encourage 'thinking outside the box' as a means of ensuring that people in the disciplines mentioned above play an active role in the 'changing water services and planning environment' mentioned in the Conference title.

CONTEXT: A CHANGING WORLD

INTERNATIONAL CONTEXT

The global environment in which people in Ireland live and operate is challenging and is constantly evolving:

- Warming of the climate system due to human influence is unequivocal (Wall *et al*., 2016); GHG emission reduction needed.
- World population is increasing, particularly in regions that are in water stress.
- More food is needed, which must be produced in a genuinely sustainable manner.
- Biodiversity and the associated ecosystem services are being reduced world-wide.
- Water quality is deteriorating in many parts of the world.
- The world's 'natural capital', both renewable and non-renewable, is being depleted, thereby posing a threat to the wellbeing of future generations.
- The means of measuring 'progress', i.e. GDP, takes insufficient account of the value of natural assets, and even worse, depletion of natural assets often increases GDP and therefore is considered as a positive economic outcome.
- There is a lack of trust in 'experts'. And, in addition, scientists struggle to influence policy and policy-makers.

NATIONAL CONTEXT

Geoscientists, and other water scientists and engineers in Ireland live and work in a context that must be thought through and managed so that an effective contribution is made.

On the one hand:

- We live in a beautiful, geologically interesting country with a relatively good environment in terms of water quality and quantity, and biodiversity.
- We produce high quality food.
- We have made significant progress in providing geoscientific[3], hydrological[4], biological, hydrochemical and catchment-based[5] datasets and information. In parallel, research outcomes are helping provide a good scientific basis for effective decision-making.
- We have developed and are using a holistic Integrated Catchment Management (ICM) approach to water management (Daly *et al*., 2016).
- We have a single public water utility – Irish Water – which is enabling greater efficiency in sewage disposal and water supply.
- In 2016, the Local Authority Waters and Communities Office (LAWCO) was established to engage with local communities and promote public participation in the management of our water environment.

On the other hand:

- Environmental Protection Agency figures show that Ireland is unlikely to meet its 2020 EU greenhouse gas emission reduction targets.

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[3] http://spatial.dcenr.gov.ie/imf/imf.jsp?site=GSI_Simple

[4] http://www.epa.ie/water/wm/hydrometrics/ and http://www.opw.ie/en/floodriskmanagement/hydrometrichydrologicaldata/

[5] www.catchments.ie

- Pressures from agriculture (nutrients, sediment, GHGs) and rising population (nutrients and BOD) are increasing.
- Water quality is not improving as required by the Water Framework Directive (WFD).
- Biodiversity and ecosystem health is disimproving.
- EU Directives, such as the WFD, and associated regulations are seen and applied as separate entities. Therefore the co-benefits from a technical/scientific perspective of considering climate change, water management, biodiversity management, flood mitigation, food production and spatial planning in an integrated, holistic manner are missed both in terms of scientific understanding, and evaluation and implementation of measures. In addition, this separation does not foster public awareness and engagement in an optimum manner.
- Achieving Food Wise 2025 outcomes, i.e. sustainable intensification, is under threat due to unsatisfactory water quality. The dairy industry and perhaps, to a lesser degree, other agri-industries regard Ireland's environment as a genuine marketing opportunity internationally in the context of challenging markets. Ireland cannot compete on scale as the farms are too small and labour costs too high; therefore, a good quality environment and 'green' image is critical to giving a competitive advantage.
- If improvements in water quality do not happen, Ireland's nitrates derogation is likely to be challenged in the medium term, thereby impinging on farm outputs, farm incomes and employment, and agri-industry.
- Our approach to environmental management is largely top down, command and control, discipline-specific, focusing on compliance of isolated components of an environmental system and end-of-pipe solutions, which in the process means '*looking at pressures in isolation and reducing environmental systems to their constituent elements when setting specific water objectives*'. [Italicised text from EC, 2012, as quoted in Voulvoulis *et al*., 2016.] While these approaches are still relevant, on their own and if used as the primary means of achieving environmental objectives, they are not effective.
- Public/community engagement on water management has been largely unsuccessful to-date; therefore this limits the 'behavioural change' that benefits environmental protection and influences public policy.
- While there have been successes, there have also been failures in public policy development and implementation in the environmental area, e.g. bog conservation.
- Policy makers in government departments and, ultimately, government ministers make the decisions that either achieve or don't achieve environmental outcomes. Currently, the knowledge transfer/exchange is a linear process between i) research outputs; ii) application of research outputs and knowledge by public body scientists/engineers to derive options and likely outcomes; iii) Departmental policy advisors; and, iv) the Minister. This linear process can be ineffective: i) scientists frequently alienate and are not trusted by policy makers because they appear to be promoting their own agendas; ii) economics is often the main driver for policy makers and politicians, and scientists seldom take account of socio-economic issues; and, iii) the knowledge transfer/exchange process is often not effective either because it is not given a sufficient priority by scientists, there is no common language or the policy maker doesn't listen sufficiently. The reality is that linking policy with science has frequently been ineffective to-date for some or all of the reasons listed above.
- Resources are, inevitably, limited.

The question arising from this context is: how should/can we, both as individuals and as members of organisations, respond?

ENSURING A SUSTAINABLE FUTURE

Several issues could be discussed under this heading; four are considered here:

- Adopting a systems approach.
- Connecting mental and structural siloes.

- Putting people at the core of environmental management.
- Economic development that is sustainable.

ADOPTING A SYSTEMS APPROACH

This provides a multi-disciplinary, multi-objective, and multi-stakeholder framework supporting a balanced evaluation of all relevant issues. Systems (integrated) thinking is a holistic approach to analysis that focuses on the way that a system's constituent parts interrelate and how systems work over time and within the context of larger systems.

CONNECTING MENTAL AND STRUCTURAL SILOES

Specialisation is considered desirable in the modern world where there is greater knowledge, better educational opportunities, more complicated technologies and larger volumes of digital data. This can encourage people to become trapped in their specialist departments, disciplines, processes, social groups, teams, or pockets of knowledge, or inside their 'silo'. Siloes exist in structures, but can also be a state of mind, that can go hand in hand with tunnel vision (Tett, 2015). Siloes, while generally comfortable for those in them, can undoubtedly be detrimental to achieving environmental objectives, particularly when the objectives themselves are based on separate regulations, with responsibilities allocated to different public bodies (Daly *et al*., 2016). By adopting a systems thinking approach and a broader 'mental model' of our roles in society, we can make the boundaries more permeable and gain from the benefits of siloes, thereby ensuring that a holistic, integrated approach is taken to environmental management, keeping in mind the quote of the American environmentalist John Muir "*When we try to pick out anything by itself, we find it hitched to everything else in the universe*".

PUTTING PEOPLE AT THE CORE OF ENVIRONMENTAL MANAGEMENT

Why?

- People are the main custodians of the environment – water, ecosystems, biodiversity, air quality – as well as being the main consumers of our natural capital and the main threat to it.
- The concepts of 'environmental management' and sustainability can only be truly viable when they take firm root in public opinion and consequently have an effect on politics and policy-making.
- This means that economic considerations are an important driver, and are, in reality, more important for most people than the concept of the 'intrinsic' value of nature.
- As a generalisation, and accepting that there are local groups with specific interests, the mental model that people in local communities have is not restricted to the interests and requirements of a specific directive or regulation or discipline area. (For instance, Boyden (2015) advocates using multiple (and creative) 'hooks' to engage people).
- 'Neutral brokers' (see Ballinger *et al*., 2016) or 'knowledge translators' (see Carton *et al*., 2016) are needed to connect the scientific aspects and findings with local communities, to link and act as a buffer between regulatory bodies and local people/communities, and to assist in leading catchment partnerships.
- However, community engagement is no guarantee of success and genuine partnerships are challenging to achieve. In addition, it can be argued that it should imply giving local communities an input to decision-making.

ECONOMIC DEVELOPMENT THAT IS SUSTAINABLE.

The phenomenal economic growth since 1950 has meant that living standards have raised; however, there are now seven billion people in the world and the effects are felt across the planet with virtually no area that is purely natural left. With a projected future world population of 9-10 billion in a heating planet, the potential consequence for water quality and quantity, and biodiversity requires treating the environment as an integral part of the economy. On the assumption that economic growth will continue, it is essential for the future of humankind that the growth path is genuinely sustainable.

Sustainability is a word and concept that is easy to agree with, particularly when we associate it with our children and our children's children. However, in many circumstances it has become a platitude, is often ambiguous particularly when associated with 'economic sustainability' and is becoming associated with 'green wash'. A major reason for this is that it is not readily measurable and therefore operationalising it has not been practicable.

A solution is to embed sustainability into '**natural capital**' as the central organising concept, as this provides a means of accounting for nature, including water, biodiversity, mineral resources, etc., and of attempting to ensure that natural capital is not diminished by human activities.

Natural Capital is one of the five types of capital from where we derive the goods and services on which our lives are based (see Figure 1). It is our 'stock' of waters, land, air, species, minerals and oceans. This stock underpins our economy by producing value for people, both directly and indirectly. Goods provided by natural capital include clean air and water, food, energy, wildlife, recreation and protection from hazards (from http://www.naturalcapitalcommittee.org/natural-capital/).

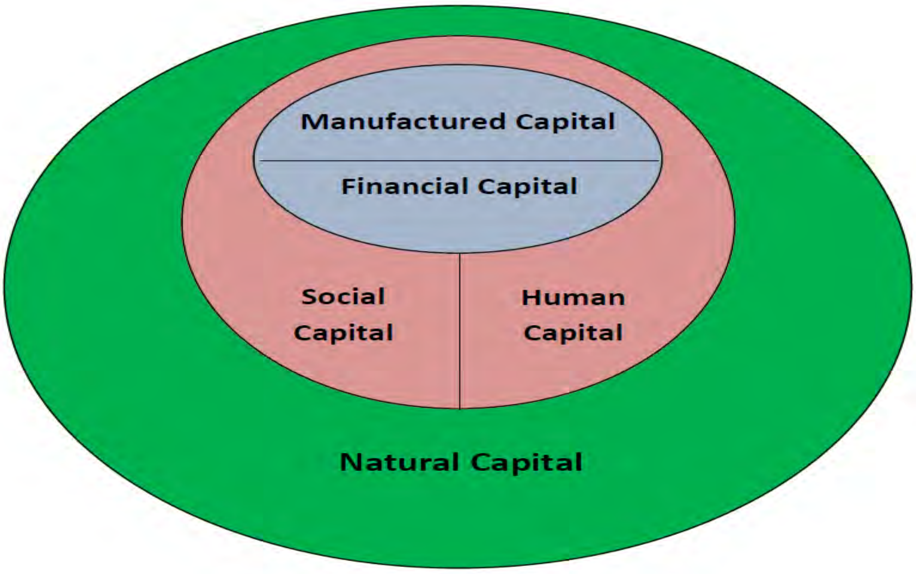

Figure 1: Diagrammatic representation of five types of capital from where humankind derives goods and services (copied from https://www.forumforthefuture.org/project/five-capitals/overview)

The natural capital approach has the following advantages:

- It is a systems and systems thinking approach thereby providing a multidisciplinary, multi-objective, and multi-stakeholder framework supporting a balanced evaluation of all relevant issues.
- It encompasses all of nature, both renewable and non-renewable, ecosystems (the communities of living organisms in conjunction with the non-living components of their environment (water and mineral soil), interacting as a system) and geosystems (the abiotic elements of nature that are not linked to living organisms – bedrock, subsoil, minerals, gas, oil, air/wind, groundwater, etc.). By encompassing all of nature (food crops, soils, subsoils, bedrock, wind, biodiversity, geodiversity, etc.) and all of the raw materials on which our economies are built, the natural capital approach helps ensure an integrated, holistic approach to decision-making. In addition, it puts the many excellent and varied projects on ecosystem services in a broader context, thereby making them more relevant.
- It requires putting an economic value on nature (renewable and non-renewable) as assets and therefore provides a means of accounting for it (Helm, 2015).
- By 'accounting' for nature, it provides the metrics on which changes can be measured, and plans and policies and actions can be made concrete. It presents an alternative and/or a parallel process to GDP as a measure of economic activity.

- It adopts what is being called 'the aggregate natural capital rule', whereby, in one interpretation at least, the aggregate level of renewable natural capital should be kept at least constant and the economic rents from the depletion of non-renewable natural capital should be invested in renewable natural capital.
- The approach means making the environment an integral part of the economy and not, as is often seen, a constraint on economic activity.

While there are advantages, there is still the need to work out how exactly our natural capital can be valued. In addition, the natural capital approach is not yet an accepted means of accounting for and managing our natural environment in Ireland.

WATER IN A SUSTAINABLE FUTURE FOR IRELAND

As a recent UNESCO publication states "*Water flows through the three pillars of sustainable development – economic, social and environmental*" (WWAP, 2015). The question is 'how do we apply this in Ireland?' The following are some suggestions.

MAKING CATCHMENTS THE 'SYSTEM' AND 'MENTAL MODEL'

The proposed definition of a catchment is as follows: **The catchment is a multi-functional, topographically-based, dynamic, multiple-scale socio-biophysical system; defined by over ground and underground hydrology; connecting land, water, ecosystems and people; and used as the basis for environmental analysis, management and governance.** This definition is intended to capture the complexity and multi-dimensionality of situations in catchments, and emphasises that catchments are not just natural systems, but have people living and working in them.

In Britain, catchments will form the building blocks of the Department of Food & Rural Affairs 25-year environmental plan and the Environment Agency and Natural England teams are being reorganised and aligned along new catchment areas (Salvidge, 2017). (The natural capital approach to valuing nature is also a feature of the 25-year plan.) This provides us with a sign-post to follow.

While catchments have been accepted in principle as the appropriate organising units for water management, the reality is that scientific work tends to be localised, dealing with specific issues, often discipline-bound and seldom connecting groundwater with surface water. Therefore, it is proposed here that there needs to be a development of the paradigm for water management that requires a clear mental image, converted to a working reality, of catchments as 3-D landscape-based units on which water management decisions, both local and regional, should be based. This, to some degree at least, is a challenge to the more traditional discipline-based approaches, including those with an interest and expertise primarily in the underground component of the hydrological cycle.

MAKING INTEGRATED CATCHMENT MANAGEMENT (ICM) THE OVER-ARCHING FRAMEWORK.

ICM involves a series of interconnected steps: (1) building partnerships; (2) creating and communicating a vision of ICM; (3) characterising the physical and ecological components; (4) identifying and evaluating possible management strategies; (5) designing an implementation programme; and (6) implementing the programme and making adjustments if necessary. This approach has the following benefits:

- It is catchment-based, aiming to connect people with their local stream, river, lake, spring, well or coastal water.
- It integrates all water types and all relevant disciplines, including social science, and attempts to link with biodiversity, flood mitigation and reduction in greenhouse gas emissions.
- It uses a broad range of 'tools' in the 'toolkit', in a continuum from local participation and partnership to enforcement.
- It requires close collaboration between relevant public bodies.

- It requires a combination of ‘bottom-up’ and ‘top-down’ approaches.
- It involves awareness-raising, engagement and consultation with local communities.
- It presents a vision of a healthy, resilient, productive and valued water resource that supports vibrant communities.
- The ICM framework fits with the systems and systems thinking approaches.

ICM features in the draft River Basin Management Plan (DHPCLG, 2017) which states ‘*A new approach to implementation called “integrated catchment management” is being used to support the development and implementation of this plan, using the catchment as the means to bring together all public bodies, communities and businesses*”. Note the emphasis on the relevance of ‘people’ in this quotation.

GEOSYSTEM SERVICES AND CATCHMENT SERVICES

While the natural capital approach and concept can provide a means of accounting for nature and of ensuring that the level of natural capital is maintained as part of a sustainable growth path, a value must be put on these assets. Ecosystem services[6] is a vital component of natural capital; it is well understood and is an area of intensive research both in Ireland and internationally. However, it does not encompass all the elements of natural capital and concentration on it alone could hinder development of the natural capital approach. Geosystem services[7] are provided by the physical or abiotic components of the environment not linked to ecosystems. Both ecosystem services and geosystem services, together with human-social system services[8] in combination form ‘catchment services’ (Daly, 2016) (Figure 2).

The value of using these three subdivisions of services within the concept of catchment management is as follows:

- It helps ensure that <u>all</u> relevant services are considered in an integrated manner, thereby assisting in achieving sustainability.
- The conceptual framework encourages linkages between water management, biodiversity objectives, land-use planning and the ICM approach. Currently, there is a tendency to treat biodiversity and water quality objectives separately, for instance in agri-environment schemes. While many measures designed for biodiversity also assist in achieving water quality objectives (including drinking water safety) and vice versa, the cobenefits are not achieved because the measures are not usually considered collectively (e.g., planting crop cover for bird species can have dual/multiple benefits provided the crop is planted in the vicinity of a stream).
- **The catchment services concept links natural capital with human/social capital and therefore builds on the intellectual, promotional and educational opportunities provided by the natural capital concept.**
- Consideration of all three types of services is necessary in preparing River Basin Management Plans as part of the implementation of the WFD.
- From the perspective of local communities, it is comprehensive and includes the complete mosaic of physical, ecological, cultural and infrastructural features and functions, thereby giving a sense

[6] The benefits that are derived from ecosystems. These include: the crops; livestock; terrestrial and aquatic flora and fauna; pollination; riparian zones for water purification; soil ecosystems for attenuating pollutants and increasing crop production; cultural values attached to wildlife; etc.

[7] The benefits that are derived from geosystems. These include: landscape geomorphology; aggregates from bedrock and gravel; groundwater for drinking water and geothermal energy; soils and subsoils as chemical and physical attenuating media for pollutants; hydrometeorology (rainfall and evapotranspiration providing the primary source of water, wind as a source of energy); geological heritage sites; minerals; oil/gas; caves; cultural values associated with landscape features; etc.

[8] A variety of social and cultural services which contribute to life within a catchment. These include: housing; farming both intensive and extensive; mining; quarrying; wind farms; water abstraction facilities; roads; landfills; industries; cultural values associated with historical features and buildings such as ring forts, castles and holy wells; water mills; pathways along streams and canals; and other recreational facilities; etc.

of comfort that no one area is dominating and that the needs of local communities are taken into account.

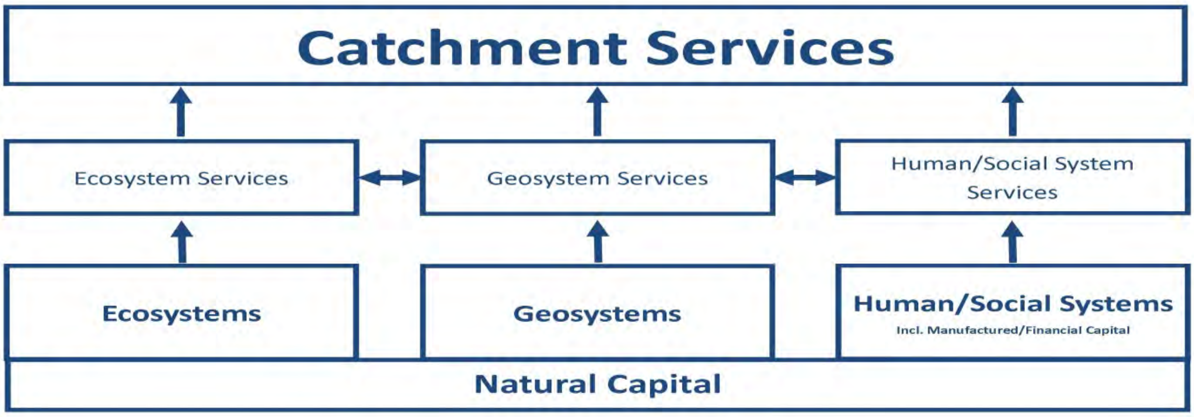

Figure 2: Catchment services encompassing the components of natural capital – ecosystem and geosystem services, and the social and economic services provided by people living in the catchment (Daly, 2016).

THE ROLE OF HYDROGEOLOGY AND HYDROGEOLOGISTS

This Section is not intended to be comprehensive, but to encourage 'looking up from the borehole' or the site or the specific research project, as appropriate, and presents for consideration some ideas that link to the issues raised in the previous section, keeping in mind that exhortations are merely words, it is actions that are needed.

THE VALUE OF SILOES!

The modern complex world needs the detailed expertise and knowledge of disciplines, and the work of specialist teams. Hydrogeologists can feel comfortable that their expertise has, rightly, become indispensible in a variety of environmental and development areas. But the problems siloes pose must be avoided. By being outward looking, respectful of other disciplines, promoting the role of groundwater only where justifiable, willing to connect with other areas and ensuring that the mental, structural and discipline silos are conquered rather than being conquered by them, hydrogeologists will have a greater impact, which will give both personal and societal benefits.

AIDING THE NATURAL CAPITAL APPROACH

The view is presented in this paper that the natural capital approach needs to be developed and used in Ireland as a means of ensuring a genuinely sustainable future for Irish people and ecosystems (including the particular streams, springs and landscapes that we all enjoy and relate to). If natural capital is to become a means of accounting for nature (keeping in mind that the requirement is that the aggregate level of natural capital should not decline), then the knowledge of geoscientists, including hydrogeologists, and the information they provide on geosystems and geosystem services, catchment services and the abiotic component of ecosystems will be essential. This is a call to take up the challenge of supporting the natural capital approach (for instance, join the Irish Forum on Natural Capital http://www.naturalcapitalireland.com/) and be willing to provide the geoscientific information needed as part of the accounting process.

VISUALISING IN 3-D

What is the most basic and yet critical advantage that hydrogeologists (and also groundwater engineers and scientists) have for the areas of environmental management and sustainable development? They can 'see' in 3-D (!). This is an enormous advantage that is not always appreciated, even by hydrogeologists. It enables hydrogeologists to understand and work with not only the purely underground environment, but also surface hydrology and the abiotic component of ecosystems. Therefore, hydrogeologists can develop, intuitively even, a mental model of the Irish landscape, over ground and underground, that is not feasible for virtually any other discipline.

HYDROGEOLOGISTS AS CATCHMENT SCIENTISTS

There are strong linkages between hydrogeologists and catchments in Ireland, particularly in the delineation of groundwater source protection zones, which require knowing the zones of contribution or catchment areas to the wells or springs. But there is not only the potential but also the need to go beyond this. Catchment science (several components of engineering are included here as ‘science’) has to be multidisciplinary to be effective. However, hydrogeologists, as both earth (over ground and underground) and water specialists, can and should contribute to catchment management, ecosystem protection (as experts in the abiotic components of ecosystems), drinking water safety plans, locating new sustainable drinking water sources, and abstraction licensing (it is likely that a licensing regime for large abstractions will be put in place during the next WFD cycle).

TRANSLATORS AND TRANSLATIONAL LEADERSHIP

Scientists by their work appreciate more than most the consequences and impacts of human activity and, together with engineers, are in the optimum position to propose the solutions that are needed to achieve environmental resilience and genuine sustainability. It is vital that objective scientific outcomes and proposed measures connect effectively with and influence both policy makers in Government Departments and public agencies such as local authorities, Irish Water and the Economic and Social Research Institute (ESRI), and with local communities, particularly farming communities who are the custodians of a high proportion of the Irish landscape. For instance, spatial planning has a major role in determining not only our daily lives, but also achievement of successful environmental management and a sustainable future.

As people who understand or have the potential to understand not only the landscape but the movement of water and contaminants on it, hydrogeologists are in a position to act as ‘knowledge translators’ of the information. The challenge for hydrogeologists (and also other water scientists, ecologists and climate scientists) is to provide translational leadership – while this might be regarded as a buzz word, it nevertheless captures the role that is needed to lead, connect, mediate, vision the future, etc., as a means of achieving agreement and the consequent changes that are required to attain the society-wide transition that is needed for a sustainable future. But putting ourselves, as hydrogeologists (or other scientists and engineers), ‘in the shoes’ of the policy maker, planner, farmer or householder is difficult for most of us; yet it is essential that we do so and provide the translation and the leadership. Concepts such as listening, having empathy with the audience, appreciating the role of economic well-being as a driver, understanding the context, genuinely engaging, developing a common language, keeping the message simple, translating information, being objective (scientists with narrowly focussed agendas either personal or based on their discipline are a turn-off for policy-makers), being transparent, appealing to the emotions and the senses, avoiding criticisms of past activities while learning from them, being realistic by setting achievable objectives, appreciating resources limitations in public bodies, learning from farmers, local communities and policy-makers, etc., must become part of our philosophy. And we all need to take this on board and not see it as someone else’s role – while some will lead more than others, we must all contribute.

ACKNOWLEDGEMENTS

Any views expressed here are those of the author and do not necessarily reflect those of the Environmental Protection Agency.

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SUSTAINABLE GROUNDWATER RESOURCE PLANNING AND MANAGEMENT

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ABSTRACT

Hydrogeology is not just about boreholes, but is the basis of groundwater resource planning and management. Up until the late 1980s abstraction licencing in England and Wales primarily involved assessment of possible derogation of other abstractor's rights, with little, or no, regard to environmental impact. When I started at Southern Water Authority in January 1975, hydrogeology was all about quantity and then quality considerations came to the fore in the late 1980s and early 1990s. Now groundwater resource planning is dominated by environmental considerations and clawing back licenced quantities to make abstractions more sustainable. Hydrogeology plays a significant role in water resource planning and management at Southern Water, as over 70% of our public water supply, (PWS), comes from groundwater. Two of our largest surface water abstractions are in Hampshire and are from the Rivers Test and Itchen with Base Flow Indices of 0.95 and 0.99 respectively, so a large MODFLOW groundwater model is used for flow simulation. SW have developed detailed hydrogeological conceptual models that allow state-of-the-art numerical modelling of complex borehole, well and adit system water supply works and environmental sensitive water bodies using refined grids and coupled linear nodes. As we can now simulate groundwater levels and flows in both pumped sources and sensitive water bodies, we are able to model time series of source outputs and environmental impacts in extreme drought and climate change scenarios using stochastically generated rainfall records.

INTRODUCTION

Southern Water supplies drinking water to two and a half million people and collects and treats wastewater from more than four million in South East England. Our supply area includes parts of the counties of Kent, East Sussex, West Sussex, Hampshire and the Isle of Wight. The vast majority of the water we supply, over 70 per cent, comes from groundwater, with up to some 23 per cent from rivers and the rest from reservoirs. Two of our largest surface water abstractions are from the Rivers Test and Itchen, in Hampshire, with groundwater from the Chalk aquifer making up 95 per cent and 99 per cent, respectively, of the base flow. To all intense and purposes these rivers can be thought of as groundwater outcrops and as such better flow simulation is achieved by the use of a large MODFLOW groundwater model, than by conventional catchment rainfall runoff models.

The South East is one of the driest regions of the UK, with an average rainfall of 730mm a year and is classified as water-stressed by the Environment Agency. The annual rainfall can vary widely from a maximum of 1,070mm to a minimum of 340mm. However it is aquifer recharge which usually occurs between October and March, that is critical to our water resources and can vary between some 400mm and 100mm.

Groundwater resource planning and management in the Southern Water area face significant challenges, including: groundwater quality, climate change, high population growth, changing lifestyles, stakeholder expectation and stricter abstraction regulations. However the biggest impact on our supply demand balance is making sure that abstractions are sustainable, that is no adverse environmental impact. Many of our abstractions have licences of right, that is the abstraction existed before the 1963 Water Resources Act and the authorised quantities were based on past outputs. Up until the late 1980s abstraction licencing in England and Wales primarily involved assessment of possible derogation of other abstractor's rights, with little, or no, regard to environmental impact. When I started at Southern Water Authority in January 1975, hydrogeology was all about quantity, increasing borehole outputs to meet the expected ever increasing demand. Then water quality considerations came to the fore in the late 1980s and early 1990s, when it was realised that groundwater was increasingly being impacted by both diffuse and point source pollution. Now groundwater resource planning is dominated by environmental considerations and clawing back licenced quantities to make abstractions more sustainable.

Southern Water has always employed hydrogeologists, originally based in both area/divisional offices and at their headquarters. When the Regional Water Authorities were created in 1974, they took over the local authority controlled Water Undertakings, the Drainage Boards and the River Authorities. This created a truly integrated organisation with one body responsible for water supply, wastewater collection/treatment, water resource planning and management. The Water Authorities not only undertook water resource planning for their own supply area, but also for the private Water Companies, as they took over the regulatory role from the River Authorities. Over a dozen hydrogeologists were employed to carry out this work, together with hydrologists and water resource engineers.

However privatisation of the water industry in 1989 led to many hydrogeologists transferring to the newly created National Rivers Authority, (NRA), the forerunner of the present Environment Agency, (EA), and the decline in water company specialists, as consultants took over the role on a need to basis. In Southern Water this trend reached its peak a few years ago, when most water resource planning was outsourced to consultants, leaving one or two hydrogeologists to oversee all the groundwater work. This has now changed in Southern Water with the creation of a Water Strategy Team, which together with the engineering function being taken back into the business, has substantially increased the number of hydrogeologists.

UK hydrogeology in the 1970s and early 1980s was all about groundwater quantity and then water quality considerations came to the fore in the late 1980s and early 1990s. Now groundwater resource planning is dominated by environmental considerations and reducing licenced quantities to make abstractions more sustainable.

GROUNDWATER AUGMENTATION SCHEMES

As an Assistant Hydrogeologist with the Hampshire Area Resource Planning Office, (HARPO), in January 1975, my first week at work was spent reading up everything I could on groundwater augmentation schemes and then being sent out to supervise the clearance and test pumping of the Candover Pilot Scheme boreholes, of the Itchen Groundwater Regulation Scheme.

The Candover valley lies to the north-east of Winchester in Hampshire, see Figure 1. The Candover scheme was developed in 1974/5 and a six month augmentation test pumping undertaken during 1976, which was the ideal year to trial the scheme as it coincided with a severe drought, with a return period of the order of 1 in 100 years. The original reason for the augmentation scheme was to abstract water from the Chalk aquifer and discharge it to the Candover Stream, close to the perennial head during periods of low flows to improve water quality in the downstream lower River Itchen, where it passes through the urban areas of south Hampshire. Local stakeholder engagement undertaken at the time included meetings in parish halls, liaison with riparian owners and mitigation of private groundwater abstraction boreholes that could be affected by the scheme. This mitigation took the form of deepening domestic borehole supplies and installing pumps on overflowing artesian boreholes at the many cressbeds in the Alresford area. The scheme was successfully promoted in 1979 without a single objection to the granting of the necessary authorisations. Upon privatisation of the water industry, the scheme was transferred to the NRA, Nowadays environmental awareness has significantly increased since the 1970s in the UK and groundwater augmentation schemes are not always looked upon so favourably as in the past. Since the original licensing of the Candover Scheme, the environmental significance and sensitivity of the area has been formally recognised with the designation of the River Itchen Special Area of Conservation (SAC). One of the species recognised in the designation is the native crayfish. The Site Action Plan (SAP) from the Habitats Directive, (HD), Review of Consents, (RoC), published by the EA in October 2007, included proposals for modifications to the Augmentation Scheme abstraction licences to protect this designated species.

HABITATS DIRECTIVE INVESTIGATIONS

Arun Valley SPA Sustainability Study Purpose

Three wetlands beside the tidal River Arun, in Sussex, make up the Arun Valley Special Protection Area, (SPA). The purpose of the investigation was to identify a sustainable abstraction regime for the Hardham groundwater wellfield and to provide support for the EA's HD RoC for the SPA. The RoC process requires that the potential impacts of fully licensed abstraction are assessed and that actions are taken to remove any risk of a licence having an adverse effect on the designated sites. To achieve this it was necessary to:

- understand the way the wetlands work;
- understand the pathway for potential impacts between the source and the wetland features (ditches and water table);
- understand the links between hydrology and ecology;
- build this understanding into a set of related models in order to make credible predictions of full licensed impacts;
- establish a sustainable abstraction regime.

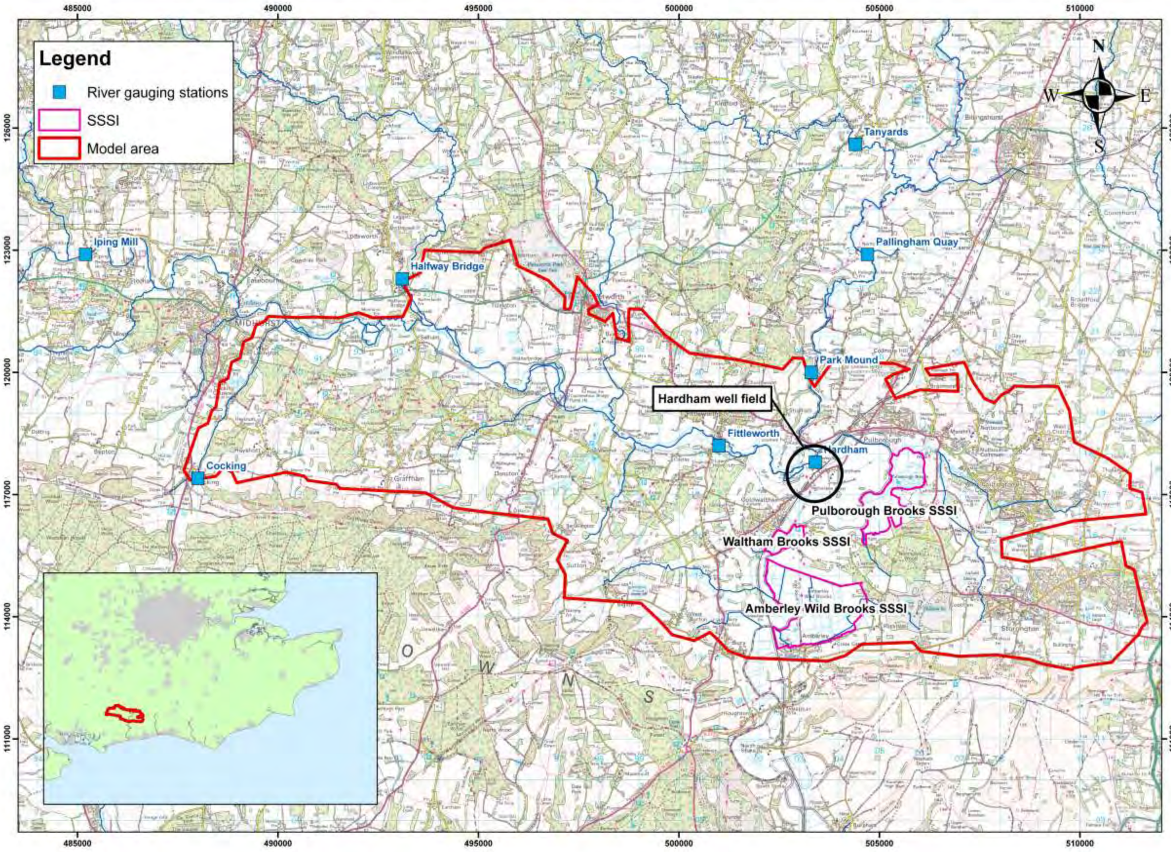
Hardham Public Water Supply Abstraction

The Hardham wellfield abstracts from the Lower Greensand, (Folkestone Beds), with a licenced daily quantity of 36.5 Ml/d. Most parties accept that the groundwater licence could not be used all the year round at the maximum rate. It is of strategic importance to Southern Water to be able to draw upon the groundwater reserve at high rates to meet peak demands and to supplement surface water abstraction during low flows, when it is constrained by licence conditions. However the Environment Agency could not conclude that there was no adverse effect from the Hardham groundwater abstraction licence on the Arun SPA.

Arun Valley SPA Conservation Objectives

One of the main conservation objectives for the SPA is to maintain, in favourable condition, the habitat for the populations of waterfowl that contribute to the wintering assemblage of European importance (shoveler, teal, wigeon, Bewick's swan) with particular reference to floodplain grazing marsh with ditches. These sub-features must be in favourable condition in order to maintain the ecological systems (principally plants and invertebrates) which are the food source for the wintering waterfowl. Thus, although the main interest features are only present in the winter, hydrological conditions for the grazing marsh and ditches through the summer are relevant to the ecological integrity of the sites.

Fig 1 Arun Valley SPA Study Area



Hardham Basin Conceptualisation

Following data collection, an initial conceptual model was developed, which was enhanced after gap analysis and additional monitoring. The conceptualisation showed that fine to medium grained soft sandstone of the Folkestone Beds are within a synclinal basin at Hardham with groundwater flow and storage dominated by the balance between recharge to the unconfined aquifer outcrop and abstraction from the confined aquifer. A large cone of depression exists in the Folkestone Beds around the Hardham wellfield and observation borehole water levels reveal a combined signal of seasonal fluctuations, due to natural recharge processes overlain by the impact of drawdown and recovery induced by fluctuating patterns of abstraction.

In the central area of the Hardham Basin the Folkestone Beds are overlain by Gault Clay and along river valleys by clay-dominated alluvium, terrace gravels and head deposits. Where the Folkestone Beds are overlain by low permeability deposits, the interactions between the aquifer and the water table, (in fields, ditches and lakes), is limited. However, where the drift is thin, or is sandy, there is greater potential for interaction between the Folkestone Beds and the water table.

There are two main pathways by which groundwater abstraction at Hardham could impact on the wetlands:

- by reducing marginal seepage to the site;
- by increasing drainage through the drift deposits that underlie the site.

Additional Monitoring

Data collected to help characterise the hydrology and hydrogeology of the wetlands included:

- Stage boards with data loggers in key surface water ditches/inflow points;
- Spot flow measurements;
- Dipwells with data loggers to measure the water table;
- Piezometers with data loggers to measure groundwater at slightly deeper levels (either in sandy drift beneath the alluvium or in the Folkestone Beds;
- Barometric loggers to allow the pressure responses in water level installations to be corrected for barometric pressure fluctuations.
- Water quality sampling and analyses

Numerical Tools

In order to quantify the impact pathway from abstraction to ecology, and to place potential impacts of abstraction into context with processes acting within the wetlands, a suite of numerical tools have been applied.

- Exploratory lumped parameter models
- Spatially distributed rainfall-recharge model ("4R" model),
- MODFLOW groundwater model
- Wetland water budget hydro-ecological models.

The hydrology of a wetland is affected by a wide range of physical processes. The wetland models are based on daily water budgets and calculations of water levels that aim to take into account as many as possible of the major processes that affect the wetland hydrology. By doing so, the models can place into quantitative context potential impacts from groundwater abstraction.

A second major feature of wetland models is that based on the best available understanding of the hydrological requirements of the interest features, they make a direct link from hydrology to ecology. The objective of the wetland modelling is therefore to:

- Assess the potential changes in wetland water levels that would result under a number of abstraction scenarios,
- Determine the potential impacts on species for which the site is designated.

WFD DRINKING WATER PROTECTION AREAS INVESTIGATIONS

Southern Water have carried out investigations at 46 groundwater and seven surface water Drinking Water Protected Areas, (DrWPAs). The investigations are to identify the conceptual understanding of source–pathway pollutant linkages to groundwater and surface water PWS abstractions, as part of the development of Safeguard Zone Action Plans.

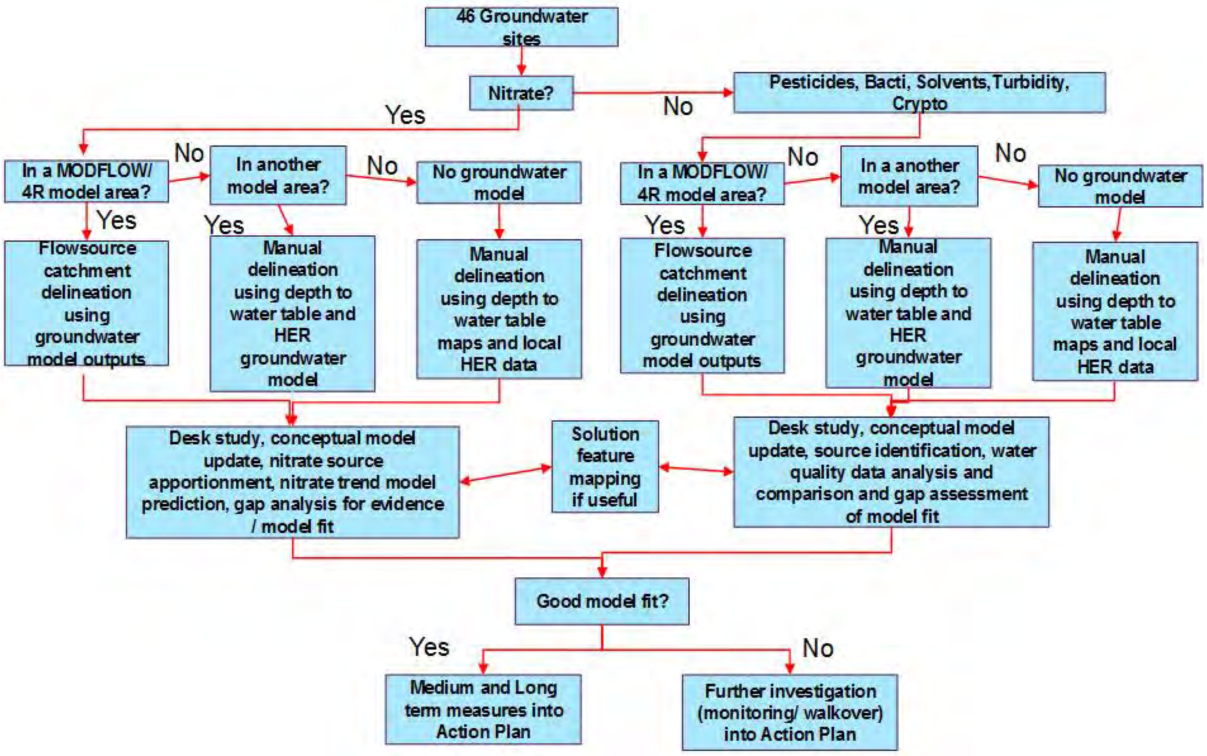
Nitrate is the main pollutant in groundwater, although pesticides, bacterial contamination, solvents, turbidity and polycyclic aromatic hydrocarbons, (PAHs), have also been identified at some specific sources. Whereas in the seven surface water catchments the substances of concern are mainly plant protection products used to control slugs and weeds in arable and pasture land, (metaldehyde, 2,4-D, MCPA, glyphosate, mecoprop, propyzamide, chlorotoluron, Benzo(a)pyrene and carbetamide).

The groundwater source investigations involved the following:

- Data collation of source and catchment specific information including time series data and spatial datasets;
- A review of water quality data including comparison with other chemical parameter behaviour and flow/ water table / rainfall / abstraction rates to identify any patterns and controlling factors;
- Groundwater catchment delineation based on actual, rather than licenced abstraction rates;
- Conceptual model development;
- Modelling of nitrate trends and source apportionment;
- Assessment of goodness of model fit;
- Working with, Environment Agency, Catchment Sensitive Farming officers and Natural England to gather further knowledge / review of outputs;

The outcomes of the work have been a series of recommendations that include some, or all, of the following: further detailed field investigations, monitoring, communications with stakeholders including advice and cost benefit assessments of potential measures to mitigate pollution. These investigations are the first step in collecting evidence to support future catchment management, and also to inform the requirement for any engineering solutions. By gathering a robust "living" evidence base and action plan, SWS will build strong foundations for justification and implementation of future planned work.

Fig 2 Types of DrWPA groundwater investigations



WFD HEAVILY MODIFIED WATER BODY INVESTIGATIONS

The Lewes Winterbourne to the north of the city of Brighton has been identified by the EA as requiring investigations to determine the impact of Southern Water groundwater abstractions on surface water flows in the Lewes Winterbourne and the associated ecology in the context of achieving 'Good Ecological Potential' under the WFD, taking into account its 'heavily modified' designation for the purposes of urban flood alleviation and amenity. The WFD Brighton Chalk Groundwater Body has also been reported as failing to achieve Good Quantitative Status because the groundwater balance tests suggest an unacceptable depletion of baseflow to dependent surface water bodies by abstraction.

The investigations can be summarised as follows: -

- Field investigations into the surface and groundwater system;
- Analysis and modelling to determine flow impacts and provide estimates of deployable output;
- Ecological investigations into the Lewes Winterbourne to determine the relative significance of abstraction related flow impacts.

Fundamental to hydrogeological understanding is the conceptual model and being able to visualise and understand systems in three, if not four, (time), dimensions, is what sets geologists apart. Any initial conceptual model should be reviewed and refined during the investigations. The starting point is a geological model, however geomorphology is often just as important. A summary of the conceptual understanding of the Lewes Winterbourne is presented below.

The Lewes Winterbourne is an ephemeral chalk stream rising in the Brighton Chalk Block of the South Downs in Southern England. The stream has developed parallel to the axis of an east-west aligned asymmetric synclinal fold feature, which underlies a basinal landform known as the Newmarket Valley. The Lewes Winterbourne drains the valley eastward to the estuary of the River Ouse and is bordered by high hills with an elevation of greater than 200m AOD to the north, south and west. The terrain is characterised by high relief rolling downland and dry valleys, the main axis of the valley floor falling from 40 to less than 5m AOD. Land use in the catchment is dominated by agriculture, predominantly pasture on the valley floors and steeper slopes with arable elsewhere. The lowermost reaches of the stream in the east are heavily modified with brick walls and culverts as it flows through the town of Lewes across the alluvial floodplain of the tidal River Ouse.

Groundwater flow patterns generally follow a subdued reflection of the surface topography, draining into the core of the Newmarket Valley before turning eastward and being discharged to the River Ouse. Seasonal groundwater level fluctuations are relatively large and can reach over 40m along the main axis of the valley and up to 30m on the interfluves to the north. Fracturing along the hinge of the syncline has combined with solution enhancement along the axes of dry valleys and dissolution associated with lower base sea levels during glacial periods, to develop a highly transmissive and productive semi karstic aquifer system along the axis of the Newmarket Valley. The aquifer also supports public water supply abstractions along the axis of the Newmarket Valley with abstraction rates of up to 30Ml/d.

Flows in the Lewes Winterbourne are closely related to upgradient groundwater levels in the Newmarket Valley. Owing to the large range in groundwater fluctuations much of the upper reaches of the stream are highly ephemeral and are typically dry from late spring through to late autumn. In some years reduced winter rainfall does not allow groundwater to recover sufficiently for the Winterbourne to flow at all and it can remain dry for extended periods (e.g. 1989-1990, and 2005-06). Flows in the summer months are rare, occurring only during periods of extreme sustained summer rainfall (e.g. 2012), when groundwater recovery is sufficient to trigger flow. Flows in the easternmost reaches adjacent to the Ouse, where the Winterbourne emerges from a culvert and flows through a local nature reserve tend to be more persistent and represent low elevation groundwater base flows.

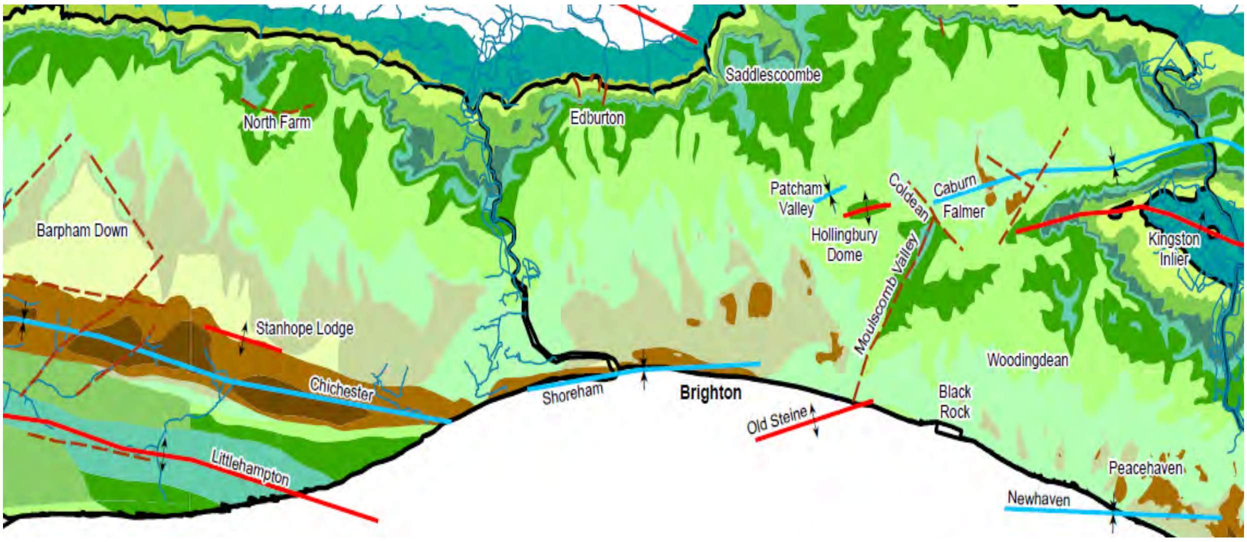
A runoff, recharge and groundwater model of the Brighton and Worthing Chalk has been developed using the 4R runoff and recharge code and the ‘Unstructured Grids’ version of MODFLOW - MODFLOW-USG. The numerical model comprises three layers of mostly regularly gridded 200m by 200m cells within which localised refinement has been incorporated around abstraction wells and along the course of the Lewes Winterbourne via a quad tree method that scales cell sizes down to a minimum of 12.5 x 12.5m.

PWS boreholes, wells and adit systems are represented by connected linear networks (CLNs) features and allow three dimensional linear features to be represented more explicitly and accurately within the model mesh than was possible previously. This allows well losses to be simulated, as well as Deployable Output constraints associated with the elevation of the pump. This, coupled with the mesh refinement, allows more accurate representation of drawdown within and around PWS abstractions.

The groundwater flow model produces a good fit to historical gauged flows in the Lewes Winterbourne, which lends confidence to its use as a predictive tool. The trigger groundwater levels at which flow in the Winterbourne occurs are also well matched. Periods of droughts in which no Winterbourne flows occurred are credibly represented, as are periods when flow is suspected to have occurred but no gauge data are available.

A general assessment of the impacts of abstraction on flows in the Lewes Winterbourne can be made by considering the difference between the two main predictive model scenarios, that for recent actual abstractions and that for naturalised (no abstraction) conditions. A key finding is that even under naturalised conditions the Lewes Winterbourne is predicted to remain ephemeral, drying every year for around 50% of the time as a long term average. Under natural conditions the duration and the maximum magnitude of flows is predicted to be greater, the average difference in predicted flow volumes being about 20Ml/d (which is of similar magnitude to the total recent actual groundwater abstraction in the Newmarket Valley The lengths of dry spells are also predicted to be shorter, by around 7 to 8 weeks each year which is a combination of both earlier groundwater recovery and later groundwater recession.

Fig 3 Brighton and Worthing Chalk Blocks – Geological Model



CONCLUSIONS

Groundwater resource planning is now dominated by environmental considerations with the reduction of licenced quantities to make abstractions more sustainable. Southern Water’s aim is to make all its PWS abstractions sustainable, especially its one hundred groundwater sources, with sound hydrogeological knowledge forming the basis of not only groundwater resource planning, but also resource management.

SESSION II

NATIONAL WATER RESOURCES PLAN

Angela Ryan
Irish Water

NOTES

KNOW YOUR ZOCs FROM YOUR SPAs – GROUNDWATER SOURCE PROTECTION TERMINOLOGY AND USAGE

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ABSTRACT

This paper aims to clarify terminology used for groundwater source protection and to highlight the degree of confidence associated with the level of assessment applied to delineating the area contributing to groundwater supply sources.

Whereas the objective of delineating zones of contribution (ZOCs) is to define approximate areas that contribute water to an abstraction point, the objective of source protection zones (SPZs) is to geo-scientifically characterise the pathway and receptor elements of risk to groundwater within the ZOC of a given source (DELG/EPA/GSI, 1999; Kelly, 2010). EPA prepared an advice note on "Source Protection and Catchment Management to protect Groundwater Supplies" that outlines the key measures and policies in place in Ireland (EPA, 2011). While these terms essentially encompass the same total area, there are differences and they should be used appropriately. It is recommended that for general usage the simplest, most basic hydrogeological term "ZOC" is used. "Source protection areas" (SPA) and "source protection zones" (SPZ) are appropriate when considering protection of groundwater sources and when a sufficiently detailed study has been undertaken in order to delineate the areas and zones. The term "Safeguard zones" is only used with reference to implementation of the WFD (Hunter Williams, et al., 2016).

1. INTRODUCTION

It is important to understand the origin of the groundwater supporting a supply source to manage and preserve its quality and quantity. Delineating the land area on which rain falls that ultimately reaches the borehole, dug well or spring is an important component of a multi-barrier approach to groundwater source protection.

There are several terms used in Ireland for the areas around springs and wells, which can lead to a certain degree of confusion. The most widely used terms include catchments, zones of contribution, source protection areas, source protection zones, capture zones and safeguard zones.

Furthermore, there are different levels of effort that can be applied in delineating the areas around springs and wells that support the flow. It is important to understand the differing degrees of confidence in the boundaries of this area that are associated with the different levels of investigation.

2. TERMINOLOGY

The main terms and phrases in use are outlined below, with a brief definition:

- **Zone of Contribution** (ZOC) is the land area that contributes water to the well or spring (Misstear *et al.*, 2006). It is a simple, intuitive, basic hydrogeological definition that is considered to be the best term for general use.
- **Catchment** is the land area that contributes water to the well or spring, or river or lake.
- **Capture Zone** is a common term present in the literature and is equivalent to the ZOC.
- **Safeguard Zone** is a specific Water Framework Directive term that encompasses the same area as the ZOC.
- **Source Protection Areas**: Geological Survey Ireland developed this terminology and the methodology for delineating the areas (DELG/EPA/GSI, 1999). Two Source Protection Areas (SPAs) are delineated which, when combined, are equivalent in area, shape and orientation to the Zone of Contribution:
    - **Inner Protection Area (SI)**, designed to give protection from microbial pollution.
    - **Outer Protection Area (SO)**, encompassing the remainder of the zone of contribution (ZOC).

3. DELINEATING ZOCs AND SPAs

Different methods can be used to map the entire Zone of Contribution to a spring, borehole or dug well (Kelly, 2010; GSI/IGI/EPA 2007, 2009), resulting in different degrees of confidence associated with the boundaries of the delineated area (**Figure 1**).

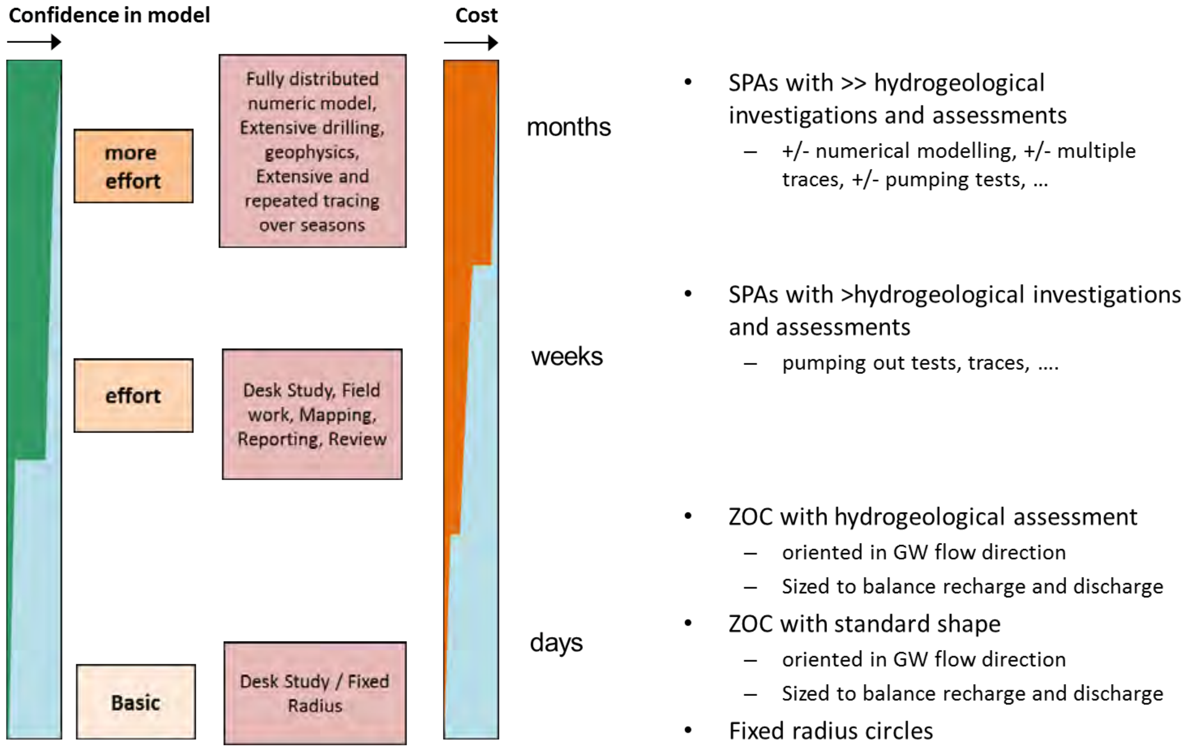


Figure 1: Relationship between time/cost and confidence in the ZOC or SPA boundary (Kelly, in GSI/IGI/EPA Source Protection Zone Delineation Course, 2007, 2009)

The ZOC and the SPA account for the 'horizontal' movement of groundwater. To be able to specify the Inner Protection Area (SI, **Figure 2**) within the entire ZOC, knowledge or estimates of groundwater travel time within the aquifer are required (e.g. from site-specific hydrogeological parameters or tracer tests).

Source Protection Zones (SPZs) are obtained by integrating the Source Protection Areas with the groundwater vulnerability categories, as shown schematically in **Figure 2**. An example of the Source Protection Zones defined for the Lipstown-Narraghmore Water Supply source is provided in **Figure 3**. The SPZ includes the complete pathway, both vertical and horizontal, for recharge and any entrained contaminants to the abstraction point.

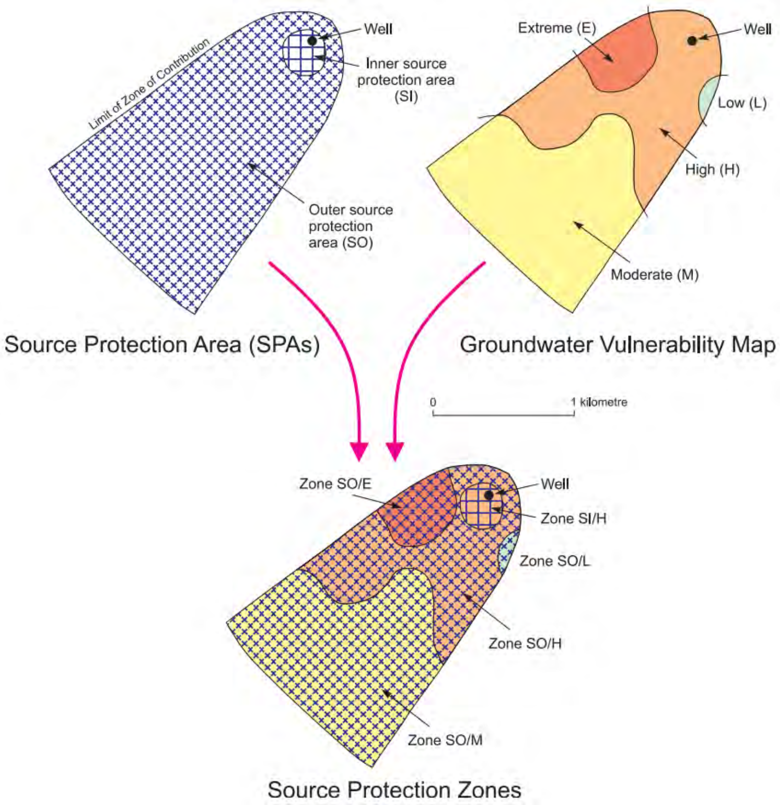


Figure 2: Delineation of source protection zones around a public supply well from the integration of the source protection area map and the vulnerability map (from DELG/EPA/GSI, 1999)

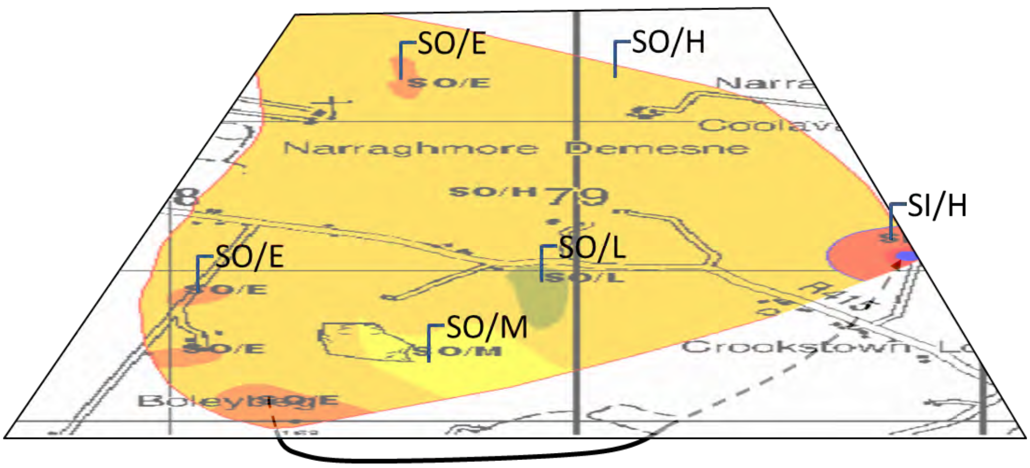


Figure 3: Source protection zones combined with groundwater vulnerability for Lipstown-Narraghmore WS spring. SI and SO comprise low, moderate, high and extreme and groundwater vulnerability (after Kelly and Fitzsimons, 2004)

4. SOME POINTS TO NOTE

4.1 SPRINGS

Like surface water bodies, springs have natural catchment areas, whereas catchment areas to boreholes depend on a number of hydrogeological and meteorological factors plus the abstraction rate. In many areas, spring catchment areas are closely correlated with topography, although in karst aquifers in certain situations, water can flow underground in conduits into an adjoining surface catchment. Spring flow typically declines over the summer months into autumn as effective rainfall decreases, but the catchment area remains virtually the same (**Figure 4**). Also, it is worth noting that springs frequently form stream or tributary headwaters and contribute extra flow to in many spring catchment areas, a proportion of the water may flow out of the catchment in streams.

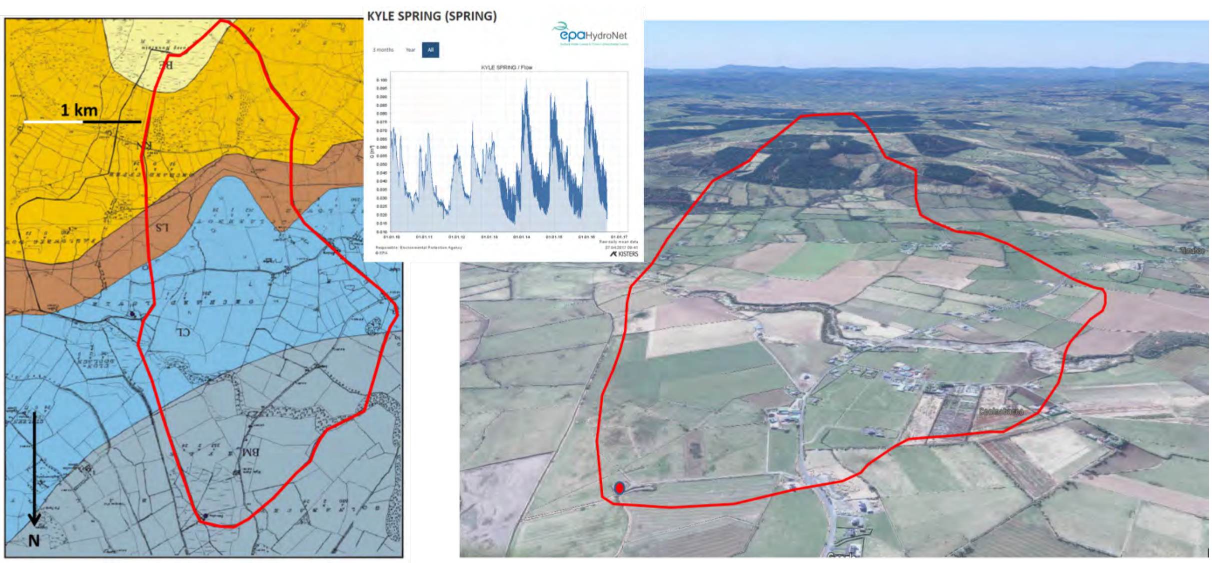
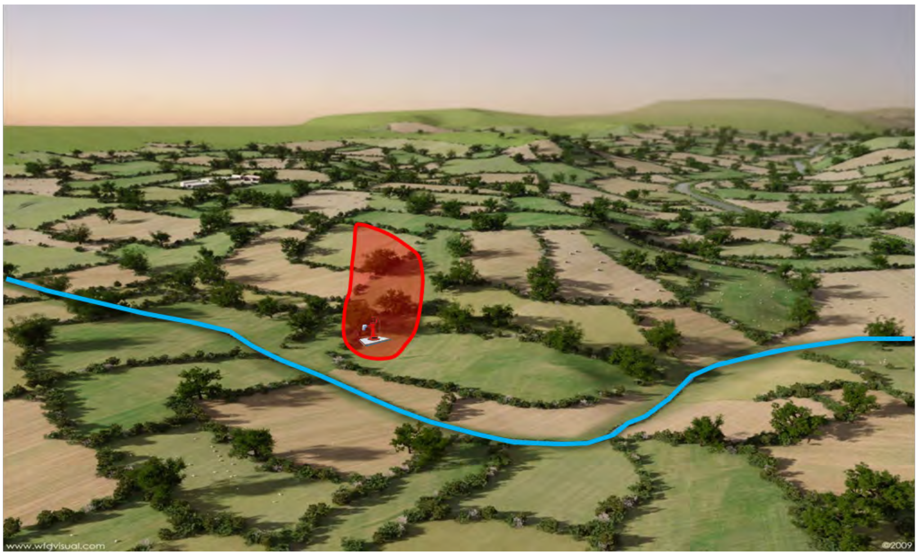


Figure 4: Catchment to a spring (Kyle Public Water Supply spring, Co. Laois) (ZOC area 4.75 km^2, McHugh and Wright, 2000; 2009-2016 max seasonal flow variation 1,210-8,726 m^3/d; average flow 3,755 m^3/d, EPA Hydronet)

4.2 BOREHOLES

The Zone of Contribution to a borehole is induced by pumping. The size of the area that contributes to the borehole depends on a number of factors, but is essentially determined by abstraction rate and by the amount of water that reaches the borehole to balance out the abstraction (the recharge) (**Figure 5**). Recharge is generally from effective rainfall, although groundwater flow can be induced from rivers or adjacent groundwater systems in response to pumping. During summer months and extended dry periods, the Zone of Contribution expands to meet a constant pumping rate. (In Irish aquifers, some boreholes struggle to meet demand after dry summers.)

a)



ZOC Area =
6.5 ha

Approximately
1 ½ fields

b)

ZOC Area =
19.5 ha

Approximately
5 fields

ZOC area	**ZOC a** 6.5 ha	**ZOC b** 19.5 ha
Recharge rate	280 mm/yr	280 mm/yr
Abstraction rate	50 m^3/d	150 m^3/d
Abstraction rate	50 m^3/d	50 m^3/d
Recharge rate	280 mm/yr	93 mm/yr

Figure 5: Interrelationship between abstraction rate, groundwater recharge rate and ZOC area to a pumped borehole (images adapted from WFDVisual)

4.2.1 Distinguishing Zone of Influence and Zone of Contribution

Unless the water table is horizontal prior to pumping the ZOC is not the same as the zone of influence of the pumping well (the zone contained by the radius of influence of the well) (Misstear et al., 2006). The zone of influence (ZOI) is defined by the "radius of influence" of a pumping well, i.e. the area where drawdown occurs due to pumping. Therefore, the ZOI boundary is where the drawdown is zero. The water table will not be flat in Ireland, therefore the ZOC and ZOI areas and boundaries will never be the same for pumping wells. In most circumstances, the ZOC will be larger than the ZOI.

The difference between the zone of contribution (ZOC) and zone of influence (ZOI) is illustrated in **Figure 5**. As shown in **Figure 5**, the ZOC boundary will extend further up-gradient than the ZOI, but not as far down-gradient.

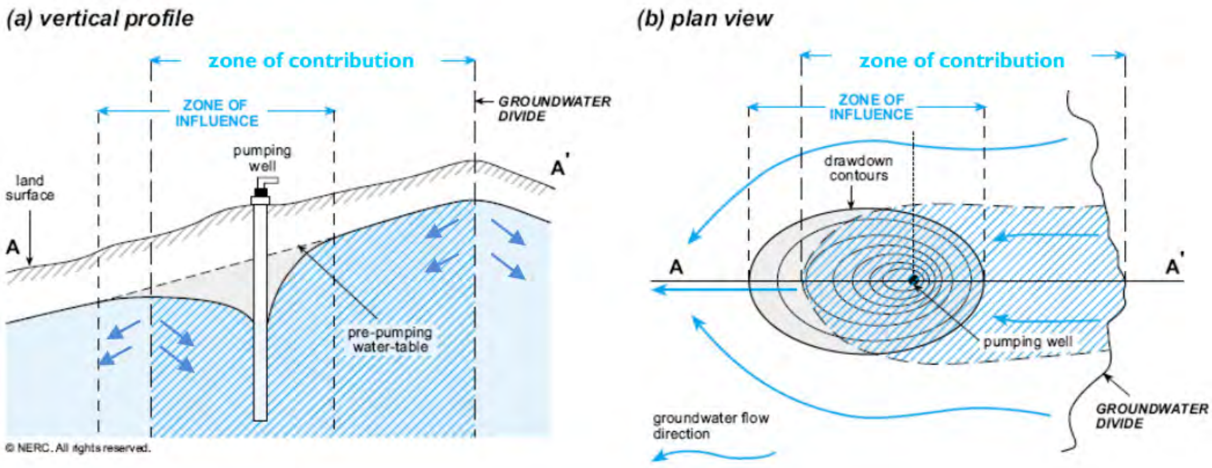


Figure 6: The difference between a Zone of Contribution (ZOC) and the zone of influence due to the interaction between the regional or local groundwater gradient and the radial flow field to the pumping well (from NERC after USEPA)

5. OTHER RELATED TERMS

Other terms in use in respect of groundwater management and groundwater protection include the following. Sometimes they are used interchangeably with the terms defined in Section 2, which can lead to confusion.

- **Drinking Water Protected Area** is a specific Water Framework Directive term and, when applied to groundwater, encompasses the same areas as Groundwater Bodies
- **Groundwater Body** is a specific Water Framework Directive term used to subdivide aquifers into effective management units, largely based on hydrogeological rules in relation to the boundaries, e.g. a ‘no flow’ boundary (GW WG, 2005).
- **Drinking Water Safety Plans** comprise a risk assessment and risk management approach to ensure the ‘safety’ and ‘security’ of a water supply. In this context ‘security’ refers to the catchment to the supply and ‘safety’ refers to the quality of the treated water meeting drinking water standards. Further details are provided in an EPA Guidance Note on ‘Developing Drinking Water Safety Plans’ (EPA, 2011).
- **Setback Distances, Exclusion Areas/Zones** are specific terms used to regulate the spreading of organic fertilisers and other farmyard activities around drinking water sources. The regulations (S.I. No 31, 2014) provide a range of setback distances from a water source depending on the daily abstraction or the number of people served. The regulations provide for alternate distances and/or zones to be proposed by a local authority or Irish Water subject to EPA approval for abstractions supplying 10m^3 or more, of water per day, or serving 50 or more persons. Further details are given in the EPA advice note No. 11 (EPA, 2011).

6. SUMMARY

The simplest and most intuitive term conceptually for the catchment area of a well/ spring is “zone of contribution (ZOC)”.

ZOC area = SPA (SI+SO) = SPZ area = safeguard zone area = capture zone.

While these terms encompass the same total area, they have different purposes. It is recommended that:

- ZOC is applied in general usage as the most basic hydrogeological term;
- SPA and SPZ are appropriate when considering protection of groundwater supply sources;
- “Safeguard zones” are referred to when considering implementation of the WFD.

ZOCs apply to the entirety of the area that supports the supply source. The methodology used and time spent deriving the ZOC can vary. Therefore, the confidence in the boundaries of the ZOC may vary. For the simpler studies, only the ZOC is delineated. The ZOC may also be derived from more detailed investigations. In this case, it will usually represent the Inner and Outer SPAs.

SPAs and SPZs can only be delineated with sufficient hydrogeological characterisation. The resultant boundaries have a higher confidence level than the simplest “ZOC only” studies (although uncertainties will still remain). The SI and SO areas combined equal the ZOC.

Groundwater ‘Drinking Water Protected Areas’ comprise the entire land surface of the Republic of Ireland as all groundwater bodies are capable of yielding more than 10 m^3/d as an average. We recommend only using this term for WFD implementation purposes.

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WATER QUALITY – PREVENTION OR CURE- A LOCAL AUTHORITY PERSPECTIVE

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Laois County Council

ABSTRACT

This paper traces the practical experience gained as an Assistant Engineer in Sanitary Services in Laois County Council (LCC) from 1980 to 1985 and more recently as Senior Engineer in Laois from April 2011 to date. The paper deals with the ***development and testing, monitoring, operation and maintenance and protection of groundwater sources****.*

The paper presents a common sense approach to the development of a risk based assessment of the potential for pathogens and chemicals harmful to public health to be present in the source. It demonstrates how prudent location, design, and construction of Boreholes in accordance with EPA Drinking Water Advice Note 14 – Borehole Construction and Wellhead Protection - combined with an appropriate pumping regime, that ideally should be steady and continuous, and with an understanding on how the site specific geology and overburden through which the groundwater recharge water percolates and contaminants are attenuated, can affect in a very positive way the quality of water entering the borehole. The paper will also show how properly maintained and protected springs, which are basically overflows from groundwater systems, and our unconsolidated aquifers through which the source water has travelled through the equivalent of a slow sand filter, can provide a high quality water supply source. Combined with this knowledge, understanding, experience and attention to detail, a holistic risk based catchment management focussing on the significant pressures in the catchment will ensure that the quality of water entering the source is such that minimal treatment is required to achieve compliance with the European Union (Drinking Water) Regulations 2014, S.I. No. 122 of 2014. This approach is consistent with the WHOs recommendation on development of Drinking Water Safety Plans and the Environmental Protection Agency's Drinking Water Advice Note No. 8.

1. INTRODUCTION

In the WHO's Guidelines for Drinking Water Quality (4th Edition) – Introduction, Section 1.1.2 in relation to Microbial aspects where it speaks about securing the microbial safety of drinking water supplies it makes the point: "*The Preferred Strategy is a Management Approach that places the primary emphasis on preventing or reducing the entry of pathogens into water sources and reducing reliance on treatment processes for removal of pathogens*" and in section 1.2.4 water resource management the WHO states "*Water resource management is an integral aspect of the preventative management of drinking water-quality. Prevention of microbial and chemical contamination of source water is the first barrier against drinking-water contamination of public health concern*". Laois is placed in a very unique position when it comes to how public and private water supplies and are sourced in Ireland. In its report on Drinking Water for Public Supplies 2015, the EPA puts the percentages for public supplies sourced from surface, groundwater and springs at 81.5%, 11.5% and 7% respectively. In Laois the corresponding figures for surface water, groundwater from boreholes and springs are 1.5%, 83% and 15.5% respectively. Of course, springs are also groundwater sources, and therefore 98.5% of the water supplies for Laois are now drawn from our groundwater resources.

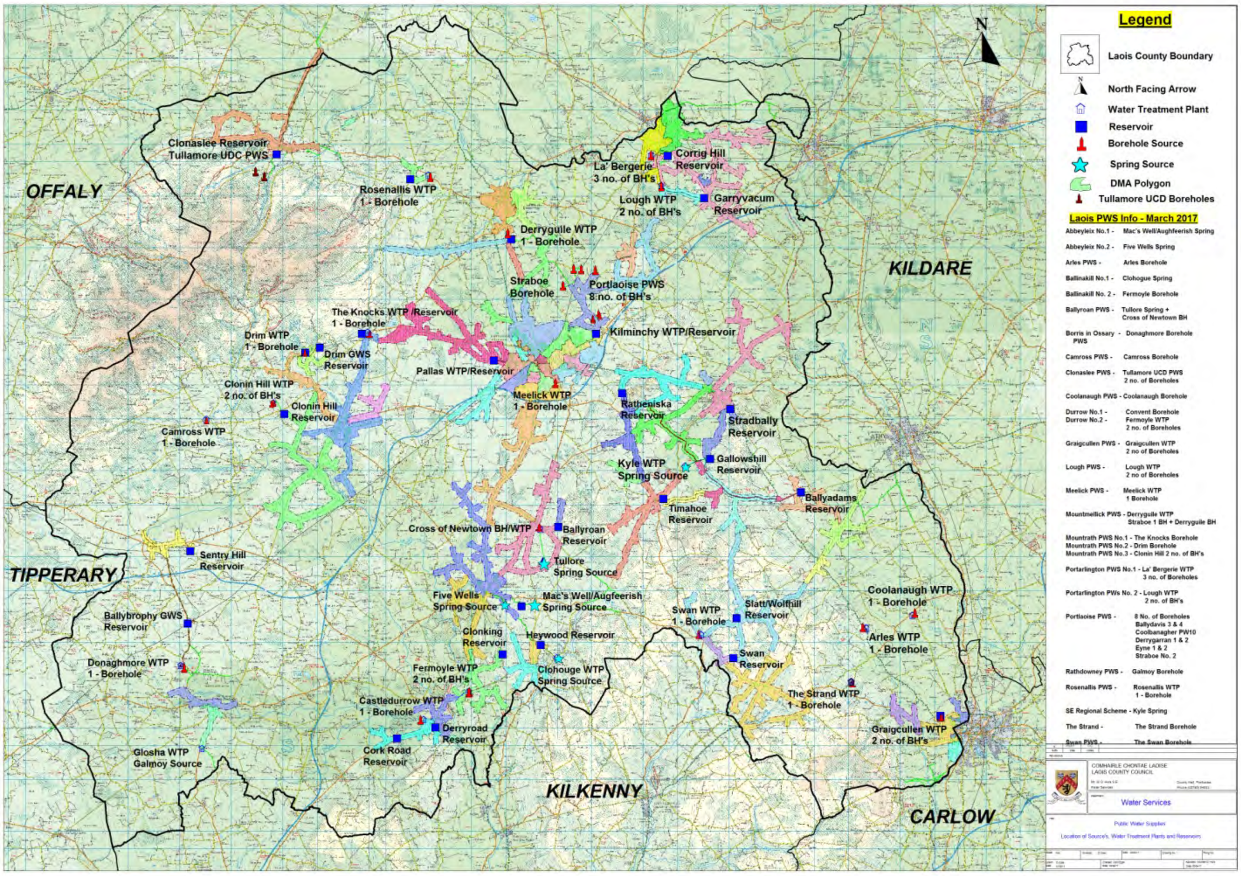

Figure 1.1 Location of all Groundwater Sources for Public Supplies in Laois

2. "THE EARLY YEARS" (1980 TO 1985)

2.1 SURFACE WATER AS THE PREDOMINANT SOURCE OF PUBLIC WATER SUPPLIES

In 1980 the picture was very different from that shown in Figure 1.1. The balance of Surface Water and Groundwater sources at this time was about 70/30 respectively. Groundwater included one borehole supplying the small town of Borris-in-Ossory, two that supply Tullamore North Public Water Supply (PWS) and Clonaslee PWS, one borehole for Durrow PWS and one borehole for Rosenallis PWS and six spring sources, including the Darkin Well – part supplied the county town of Portlaoise. Portlaoise and Mountmellick PWSs were supplied from an upland surface water source located in the Slieve Bloom Mountains, called The Catholes (see Figure 2.1). Drinking water quality varied considerably and was very poor by today's standards with detections of *E* coli not an infrequent occurrence. This was due to inadequate protection of sources, inadequate treatment processes and poor disinfection. In some of the smaller schemes, the only form of disinfection was accomplished by the Caretaker pouring Sodium Hypochlorite into the top of the reservoir. In the case of the Catholes, the only treatment was by means of slow sand filtration and disinfection by chlorination. During heavy rains, the water supply was seriously discoloured and this gave rise to customer complaints. Trihalomethanes (THMs) "*did not exist*". A biological layer called the "Schmutzdecke" develops on the surface of the filter and this assists in removing microorganisms.

Figure 2.1 The Catholes showing the intake on the left and the slow sand filters on the right

The Darkin Well that supplied Portlaoise became contaminated in 1993 by hydrocarbons, and was made redundant. In the case of Portarlington, the supply came from the Barrow River and treatment was by coagulation and flocculation followed by rapid gravity filtration. In relation to groundwater, the five Spring sources in existence to this day are: at Kyle, which is the source of the South East Regional Water Supply Scheme, Aughfeerish, Tullyroe Springs and the "5 Wells" supplying Abbeyleix PWS, and Cloghogue spring supplying Ballinakill PWS. The quality of the source water in these springs was considered so good that some of these supplies were not chlorinated. However, by 1985 LCC had rolled out rudimentary automated disinfection by chlorination on all public water supplies.

2.2 LAOIS COUNTY COUNCIL EMBARK ON DEVELOPMENT OF GROUNDWATER RESOURCES

In 1982 or thereabouts, recognizing the superior quality of groundwater as a source of drinking water and in consultation with, and on the advice of Eugene Daly (RIP), Hydrogeologist in the Geological Survey of Ireland (GSI), LCC made the strategic decision to switch its focus away from surface water as a source of drinking water to groundwater. Eugene recommended that LCC carry out exploratory drilling in a number of locations throughout the County. Electrical Pump Services Ltd. at this time supplied specialist mechanical and electrical service to Laois County Council, and they decided to invest in a substantial rotary drilling rig to carry out the exploration drilling programme. It is important to understand at this point that, albeit source water quality was an important factor in the decision of LCC to develop groundwater sources, the primary driver in the decision was meeting water supply demand. The emphasis was on Quantity rather than Quality. In Portarlington, for example, the surface supply was so inadequate that water was turned off every night by the caretaker, to the chagrin of the residents of Portarlington. The flow in the River Barrow was so low during dry periods in summer that the river had to be sand-bagged to raise the river level to cover the pump intakes.

The following Borehole Sources were developed between 1983 and 1984:

- Lough – Portarlington PWS and Lough PWS (Killenard) – 2 No. Boreholes
- Derryguile – Mountmellick PWS
- Fermoyle – Ballinakill 2 PWS and Clonking GWS and later Durrow 2 PWS – 2 Boreholes.

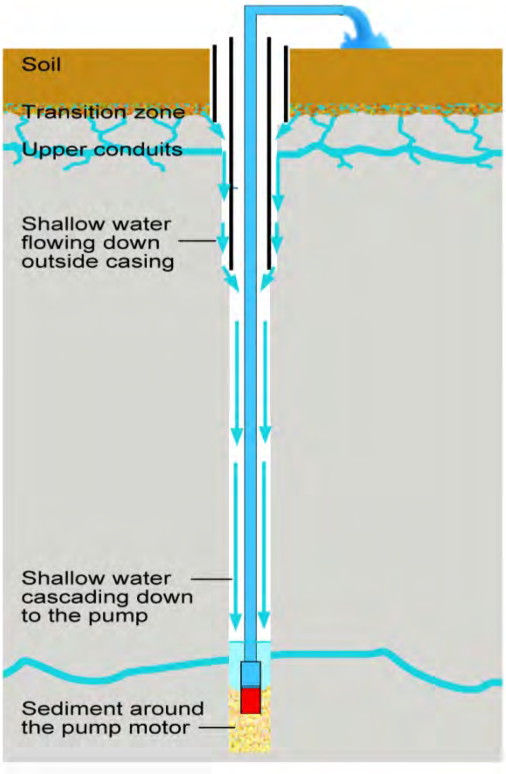

Figure 2.1 shows a section through an old borehole

Figure 2.2 is the wellhead above an old borehole

Please note that shallow water in the upper layers above the sound bedrock and in the transition zone is capable of flowing down the sides of the permanent steel outer casing. This allowed contaminants in the shallower water to enter the borehole.

In the case of the development of the original boreholes at Lough, it was anticipated that the main source of supply of groundwater would come from a major fault separating the Allenwood and Calp Limestones. (The drilling of new boreholes in the early 2000s, supervised by David Ball, actually showed that this was not the case. Instead, the prolific flow of groundwater came from a thin, but extensive, gravel deposit above the bedrock and below thick clays.) The driller of the original Lough boreholes in the 1980's, in his efforts to get bedrock groundwater, actually tried to seal off the sand and gravel water but because he did not use a cement seal around the casing the groundwater from the gravels flowed under the casing into the hole.

Another important feature of the construction of boreholes in these early years, was the ill-considered practice of placing the pump near, or on, the bottom of the borehole. The rationale for this was based on a lack of understanding of the basics in groundwater flow and hydrogeology, not knowing how to construct and maintain boreholes or where to place the pump or developing sustainable pump operation regimes. The idea for placing the pump near bottom of the hole was in believing that by so doing, the pump would be protected from the drop in water levels during prolonged dry spells. In fact, excessive drawdown usually took place because a big powerful pump was installed, this resulted in short periods of intense pumping sometimes with high turbidity levels, or if an ill-advised screen had been installed, of the screen and any gravel packs became clogged which lead to increased drawdown, and often this inappropriate pumping resulted in particulate matter being drawn into the borehole. This sediment, over time built up to such a level that the pump motor became surrounded by sediment. It was not cooled by a circulation of fresh groundwater, and hence over-heated and either tripped out, or burned out. Many experiences of trying to drag such pumps out of boreholes remain vivid in Local Authority Engineers' minds to this day. The fact that the pump was positioned in the open hole below much fractured bedrock, resulted in many cases of having to abandon the borehole due to the unsuccessful attempts at trying to retrieve the pump from the hole, when a stone or coarse gravels from upper cavities prevented the pump from being raised.

Nevertheless, the success in developing these resources meant that, in the case of the Lough boreholes, Portarlington had inadvertently obtained an adequate supply of good quality water to meet demand. The second borehole at Lough was able to supply Killenard GWS. This large group scheme was then able to abandon an old spring source which had been contaminated by discharge from domestic waste water treatment systems. In the case of Derryguile, the new borehole source replaced the old supply from The Catholes. The development of two new, but shallow boreholes at Fermoyle provided much needed water supply to the village of Ballinakill and became the source of the supply to the proposed Clonking GWSs. In the case of Fermoyle, 72 hour pumping tests suggested a safe yield of 1.8MLD. When the Clonking GWS submitted the scheme to Laois County Council, pipe sizes were increased to cater for the future development of the scheme into a Regional Water Supply Scheme that would be capable of supplying/augmenting the supply to the towns of Durrow, Ballinakill and Abbeyleix. With funds from the DoE all these schemes were completed before 1985. Consequently, by 1985, the balance of water supply had shifted towards Groundwater away from Surface Water 2 to 1 in favour of Groundwater.

3. "THE LATER YEARS" (2011 TO THE PRESENT)

3.1 PUBLIC WATER SUPPLIES

3.1.1 Pre Irish Water

In April 2011, as Senior Engineer in Roads, I moved to Water Services in Laois. Following from the EU DW Directive 98/83/EC and the Water Framework Directive 2000, subsequent national legislation followed under which LAs were the Water Services Authority (WSA) under the WS Act 2007 and Water Supplier under the EC (DW) (No. 2) Regulations 2007 for all PWSs. In relation to public health and the quality of drinking water, Section 4 of these regulations pertains to *Duties of Suppliers* which are:

2. (1) Subject to any departure granted under regulation 11, a water supplier shall ensure that the water is wholesome and clean and meets the requirements of these Regulations.

(2) For the purposes of paragraph (1), water shall be regarded as wholesome and clean if –

(a) It is free from any micro-organisms and parasites and from any substance which in numbers or concentrations, constitute a potential danger to human health, and

(b) It meets the quality standards specified in Tables A and B in Part 1 of the Schedule.

As the Supervisory Authority for PWSs, the Environmental Protection Agency (EPA) among other powers can direct a water supplier to meet these quality parametric limits (section 10 (4) (a)) and has powers of prosecution if a water supplier fails to comply with such directions Section 22 (1).

It was clear that public health and the provision of a safe and dependable water supply, which would ensure that water was fit for human consumption, was paramount.

Laois County Council, with funds from the DoE, and its own funds had continued the trend towards developing further sustainable groundwater sources in preference to Surface Water Sources. I, and some of my predecessors in Water Services, had realised that though Laois has several big rivers the water in these rivers is inherently dirty and requires expensive treatment. We also realised that the base flow in these rivers, upon which we depended to maintain a year round supply, is made up wholly of groundwater. Progressively, I and my predecessors realised that it is much more cost effective and easier to take the naturally purified groundwater before it gets to the river and becomes mixed with 'dirty river water'.

By about 2000, only four surface water sources remained in the County; – The Catholes supplying Mountmellick PWS, the Ballymorris Plant supply from the river Barrow continued to provide 600m^3 per day to Portarlington, the Tullamore Urban District Council plant in Clonaslee, from which

Clonaslee continued to be supplied. Graiguecullen PWS received its water supply from Carlow UDC which provided a blend of surface water and groundwater. The EPAs report on quality of drinking water in Ireland 2011 included one scheme in Laois on the RAL. This pertained to the Mountmellick PWS which was part supplied from the Catholes. The levels of TOC and DOC in the source water were such that the parametric limit for THMs was frequently in breach of the parametric limit of 100mg/l in the DW Regs. LCC commissioned Ryan Hanley, Consulting Engineers, to carry out an assessment of the resource and to consider the options for upgrading the plant to ensure that the parametric limit for THMs could be maintained at levels below the 100mg/l limit. The Consultants concluded that the options were very limited and very costly. As regards Portarlington PWS, the old Plant at Ballymorris, while meeting the compliance requirements of the regulations, it was considered high risk from a quality point of view, a high risk from an environmental viewpoint due to the lack of proper used alum storage lagoons not to mention considerable health and safety risks. Consequently, a decision was made to substitute these 2 schemes by substitution from groundwater sources.

In relation to Health and Safety, central to developing a Safety Management System is developing risk assessments and in so doing having regard to the General Principles of Prevention as described in Schedule 3 of the SHW Act 2005. In this schedule it outlines such measures of avoiding the risk by eliminating the hazard, the combating of risk at source etc. This approach sits very well with the development of drinking water safety plans strategically and in a very common sense way, reducing risk or actually eliminating risk altogether.

From 2000 to the present day there have been a series of groundwater exploration and development programmes. These programmes have been carried out either by, or with the help of, many members of the groundwater community in Ireland.

Portlaoise Water Supply is now entirely supplied from a new wellfield to the north and north east of Portlaoise, which had been developed between the mid 1990s and 2008. The safe yield from the Portlaoise Limestone Aquifer (PLA) in which the wellfields had been developed is estimated to be 20MLD (Nicholas O'Dwyer and Partners – Laois County Council EIS).

In 2013 under the DoE's WSIP - LCC sought and secured funding from the DoE to bring one of the surplus wells – Coolbanagher No. 10 into production, thus replacing the surface water source at the Catholes with a high quality groundwater. The contract was completed in 2014. Subsequent analyses of the water supply from the new borehole confirmed compliance. IW sought and had the THM matter removed from the EPAs RAL list.

In 1999, David Ball, was commissioned by LCC to explore new groundwater sources near Portarlington. After a hiatus between 2002 and 2006, David Ball worked with Patrick Briody and Sons to site, design construct and test three new wellfields for Portarlington at Doolough, Lough and La Bergerie.

One borehole at La Bergerie was immediately brought into production and in 2008 a second borehole was brought into supply. Eventually in 2012 LCC decided to replace the old Ballymorris Plant by bringing both the Lough and La Bergerie Wellfields into production.

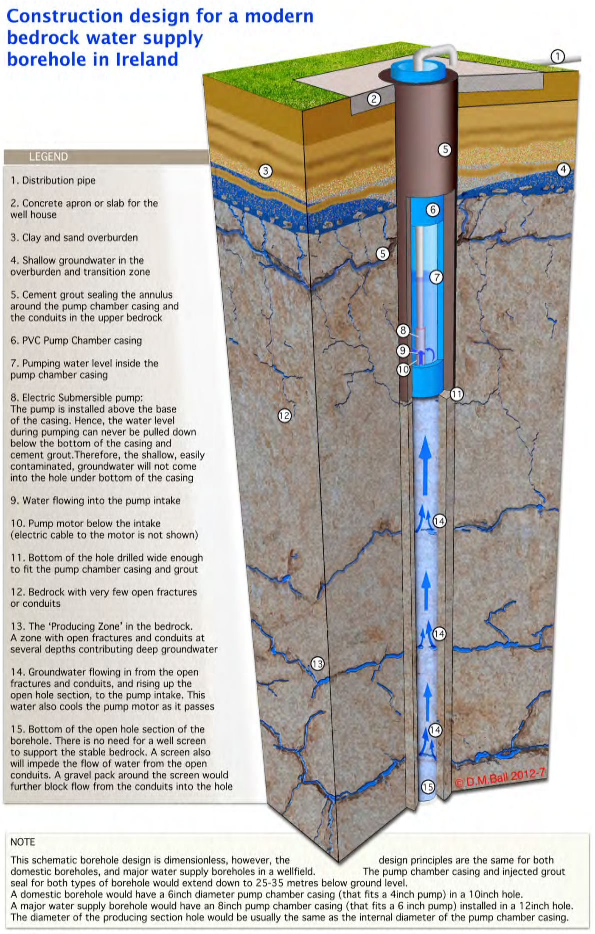

Figure 3.1 above is a 3D represesentation of a new Borehole constructed in accordance with EPA Advice Note 14 – Borehole Construction and Wellhead Protection

Figures 3.2 shows a modern control Kiosk mounted on top of a wellhead pad

Between 2012 and 2013, LCC invested €1.5m in rolling out a county-wide Supervisory Control and Data Acquisition (SCADA) system covering all water treatment plants in the County. The real-time and historical data on flows, water levels in boreholes, raw water and treated water quality and effectiveness of disinfection systems which became available, has proven to be an invaluable tool in ensuring compliance with the DW Regulations, analysing trends and in decisions on improving and investing in upgrades to the plants.

3.1.2 Post Irish Water

From 1st January 2014 the responsibility for the provision, operation and maintenance of Public Water Supplies transferred to Irish Water (IW) under the Water Services (No. 2) Act 2013. The Local Authority (LA) from this date operates and maintains the public water supplies as an agent of Irish Water under a Service Level Agreement (SLA) signed by each LA and IW. The EPA remains the Environmental Regulator.

In 2014 Laois was asked to apply the EPA's 'Risk Screening Methodology for Cryptosporidium' contained in Drinking Water Regulations Guidance Booklet No. 4 2008. As a result of this desk exercise, in late in 2014, the EPA added Portlaoise Water Supply Scheme to its Remedial Action List (RAL) for "inadequate treatment of Cryptosporidium".

However, LCC since 2012 had initiated a programme of “Raw Water” monitoring. Included in this programme were all the production wells in the Portlaoise Limestone Aquifer. In 2013 LCC initiated a programme of “Raw Water Monitoring” Samples of untreated water from all the production boreholes were sampled four times per year for Microbiological and chemical analyses. The results demonstrated that the quality of the source water entering the boreholes in the PLA was of very high quality with only 2 cases of detections of coliforms - one case of a detection of just 1 *E.* coli. From 2013 four samples of treated water were sampled for Cryptosporidium and all samples were negative for cryptosporidium. Consequently, based on the knowledge of the standard of construction of the boreholes, and on the evidence gathered over the three year period, IW and LCC drew up contract documents with appropriate Terms of Reference and went to the market to engage a Consultant Engineer with strong Hydrogeological competency to carry out an ‘Evidence Based Crytosporidium Risk Assessment’. Jacobs Tobin was awarded the contract. A methodology was developed to deliver on terms of reference in the contract. An interim report was submitted to the EPA in February 2017 and a final report is due for submission to the EPA later this year.

In 2013, Treated Water nitrate trends in the supply from the Fermoyle shallow boreholes were showing evidence of rising above the parametric limit of 50mg/l in the DW Regulations. In 2014 this parametric limit was exceeded and nitrate levels were continued in an upward trend. In conjunction with IW, LCC and David Ball, decided that the best long-term strategy for dealing with the increasing nitrate levels was to try to reduce the input of nitrogenous matter in the catchment and also explore the deeper groundwater resources to find out whether nitrate levels decreased with depth. The possible outcome might be the discovery of groundwater with lower nitrate levels and the replacement of the two old boreholes, which are unsealed and drawing upon shallow groundwater.

Whilst waiting for approval to carry out the exploration drilling programme, IW and LCC provided a temporary nitrate reducing plant which maintains the level of nitrates in the DW below the parametric limit.

For the long-term solution, the Phase 1 desktop and field reconnaissance and surveys and Phase 2 – the drilling of exploratory boreholes -have been completed and Phase 3 – the drilling of new production boreholes - is pending following results from some further testing to establish whether the deep groundwater nitrate levels are sustainable over time. A very important and essential ingredient in this study was the choice of driller and the equipment and the benefit that a well-experienced driller brings to such a study. The particular rig used here employed 300mm symmetric casing that follows down the hole with the drill bit. This allowed samples of water to be obtained at discrete depths in the drilling process for analyses of nitrates.

From a source protection point of view, LCC has carried out farm inspections in the catchment and are working with local farmers in putting in place measures to reduce the input of nitrates into the groundwater. The local farmers have been very understanding and one of the measures that have been adopted is to hold back as long as they can on spreading slurry in the catchment until soil temperatures are such that the nitrate is used up effectively. There is a piggery in the catchment and again, co-operation with LCC, the owner and his advisor is paying dividends. The owner has agreed to send his slurry to farmers outside the catchment. He is also providing monitoring boreholes around his unit so as to identify if there is any seepage from the holding tanks in the piggery. Domestic Wastewater Treatment systems have been inspected in the catchment and where necessary improvement notices have been served.

3.2 PRIVATE WATER SUPPLIES

3.2.1 EPAs Focus on Private Water Supplies in 2015

Almost 20% of people in Ireland get their drinking water from private supplies and the 4 categories are: Public Group Water Schemes (2%); Private Group Water Schemes (4%); Small Private Supplies (SPSs) with a commercial or public activity (1%) and Household Wells (10%). In relation to Water Quality, the EPA puts the figure of compliance for E Coli nationally at 96.3% compared with a figure of 99.92% for Microbiological compliance in PWSSs. As Public Schemes generally comply with the requirements of the DW Regs as they receive their water supply from the PWSs, I will confine this section to the latter three categories. In Section 2 of the EPA's report, it confirms that Water Quality is Consistently Poorer in Private Supplies.

3.2.2 Private Group Water Schemes:
LCC, in its role as Supervisory Authority under the EU (DW) Regs 2014 has always had and continues to have a very good working relationship with the Group Water Schemes, their members and work along with the National Federation of Group Water Schemes to support and advise the Private Group Water Supply Schemes (PrGWSs), technically and with the support of the DoHPCLG financially, to improve the quality of water in their schemes. All schemes in Laois receive their water supply from groundwater, so in general, the quality of drinking water in Laois PrGWSs is very good.

3.2.3 Small Private Supplies (SPSs) have the poorest quality
The EPA put the compliance figure nationally at 94.8% for compliance and I would suggest that it is a lot worse than this as monitoring of SPSs nationally is poor. LCCs experience in supervising and monitoring these supplies points to a serious lack of understanding of the importance of providing a safe source of water and indeed that very serious public health consequences associated with supplying water that is contaminated with *E* coli. In one case in Laois, the presence of *E coli 015* in the water supply led to a serious outbreak of VTEC in the residents of a private housing estate. LCC are aware of the poor standard of construction of boreholes – one case where a large commercial operation which also served a private housing scheme with 100 units had its wellhead sunken into a car park and covered in un-sealed chamber cover. Another example was a small commercial operation where the wellhead was not to be seen – it was buried under the lawn.

In its report, the EPA estimates that there are 170,000 household wells in Ireland and of these; it estimates that 30% are contaminated by *E* coli. The corollary of this is that there are 51,000 household wells that are providing a direct route for faecal contamination of the groundwater.

3.2.4 What can be done?
Article 11 (e) under Programme of Measures in the WFD imposes on each member state to put in controls on abstractions from fresh surface water and groundwater but goes on to allow exemptions to be made for abstractions *"which have no significant impact on water status"*. Section 7.7 of the Public Consultation Paper on River Basin Management Plan for Ireland (2018 – 2021) – Addressing abstraction pressures deals with this area. In section 7.7.2 – Programme of measures to address abstraction pressures it develops a basis for registering all abstractions and some more binding rules above 25 m^3 per day and for those above 250 m^3 per day it is proposed that licensing will be required. As most of the SPSs and some of the PrGWSs are below the 25 figure, most SPSs and all household wells will be exempt.

3.2.5 The National Rural Water Review Group
This group has been formed with representation from LAs, NFGWSs and the DoHPCLG to identify a model which will achieve efficiencies and improved service delivery to the Rural Water Sector, in full compliance with the DW Regs and LA's statutory role as Supervisory Authority, while also being cognizant of the transformation of the Public Water Services. The model must build on and enhance the partnership approach between LAs, the NFGWS and GWSs to deliver a consistent level of service across the country that is sustainable and instils public Confidence. As project manager of the Project Team, I aim to bring my experience and knowledge to this project to ensure that the final delivery model improves the quality of water in Private Supplies and an improved consistent service across the Sector.

3.2.6 How can we ensure that Private wells are compliant with the IGI Water Well Guidelines.
As long as it is essential to drill in 8" to ensure that there is adequate sealing of the annulus around 6" permanent casing to adequate depths which will require €5,000 to be spent by the person needing the well, the alternative construction with 6" drilling and inadequate sealing of the annulus for €2,500 will continue. Putting conditions in planning permissions will not succeed. An alternative must be sought.

4. Conclusions

Laois has surface water resources, but has made a decision to develop and exploit its groundwater resources. It has done so because the County has limestone aquifers with a good protective covering of soil and glacial deposits. This means that in most areas these hydrogeological conditions naturally treat or remove any contaminants and by-products in the recharge. The gradient on the groundwater system in lowland Laois is small. Therefore, groundwater moves slowly. The combination of protective soils and slow groundwater flow means that properly sited and constructed boreholes can draw upon groundwater that does not require treatment to remove anthropogenic, or agriculture related contaminants. Chlorine need only be added to protect this high quality water. The decision by Laois to use groundwater is a common sense decision backed up by applied science.

Therefore, the answer to the question posed in the title of the paper; is that in Laois we can Prevent. If we do our groundwater work properly, we do not need to Cure. Prevention is also a lot less expensive than cure.

TOWARDS ENERGY-EFFICIENT WATER WELLS THROUGH OPTIMIZATION OF WELL HYDRAULICS

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ABSTRACT

The energy demand of water wells is an effect of the sum of the head losses caused by its individual components: (a) aquifer, (b) wellbore skin, (c) gravel pack, (d) screen slots, (e) screen and casing interior, (f) pump and installations above. Flow velocity increases from (a) to (f), inducing a transition from linear laminar (Darcian) flow in the aquifer, to non-linear laminar (Forchheimer) in the gravel pack and finally to fully turbulent flow in components (d) to (f). A spreadsheet calculation tool was set up to calculate these losses for steady-state radial flow in a confined aquifer. The most important losses occur in the aquifer and the wellbore skin, if present. The removal of the latter is thus the best option to optimize the well hydraulics. Practical experience has shown that many submersible pumps operate far from their ideal operating point, which also reveals a significant potential for improvement.

INTRODUCTION

The energy demand of water wells is often overlooked when considering the impact of groundwater extraction (Houben et al. 2015a). Indeed, in industrialized humid countries with shallow groundwater tables and little need for irrigation, water wells contribute little to the total electrical energy demand (Germany: 0.5 % of primary energy consumption). However, any improvement is welcomed in the strive for improved energy efficiency and the transition to greener energy. In more arid countries, irrigation with groundwater may be imperative to sustain agriculture, resulting in the construction of innumerous wells. Water levels in such countries are often quite deep (often a result of the extraction itself), requiring a high lift energy. In combination, this leads to substantial energy demand. India, for example, uses around 20% of the total electrical energy produced in the country for the operation of 20 million wells, most of them irrigation wells. Additionally, billions of liters of combustible are being used to power shaft-driven pumps. Even a slight improvement of the energy efficiency of these wells will result in a massive saving of cost and a significant reduction of the carbon footprint.

DRAWDOWN AS MEASURE OF ENERGY EFFICIENCY

The energy demand of a water well is a function of the lift (height) that the pump has to overcome. The total drawdown measured in the active well is the sum of the drawdowns caused by its components. They comprise: (a) aquifer, (b) wellbore skin, (c) gravel pack(s), (d) screen slots, (e) screen and casing interior, (f) pump and installations above (Houben et al. 2015b).

Due to the continuous decrease of area towards the well axis, the flow velocity increases from (a) to (f), inducing a transition from linear laminar (Darcian) flow in the aquifer and the wellbore skin, to non-linear laminar (Forchheimer) in the gravel pack and finally to fully turbulent flow in screen slots, screen and casing interior and pump. Flow velocity can be manipulated to some degree by varying the area of the well components, e.g. by enlarging the drilling diameter (or the slot size) or by extending the screen length (Houben et al. 2015a). The effects are, however, strongly limited by the increase in cost incurred by larger and deeper wells.

The losses of the aquifer are a function of its hydraulic conductivity, which is given by nature and can only be improved marginally by well development or, in some cases, by hydraulic fracturing. Fines stemming from drilling additives like bentonite but also from clay particles from penetrated aquitards can be deposited at the borehole wall during the drilling process (wellbore skin). Despite its usually small thickness, wellbore skin can induce losses in the same order of magnitude as the aquifer, if not removed properly during well development (Houben et al. 2016). Losses in the gravel pack are usually in the range of centimeters. They can be optimized to some degree by reducing the flow velocity so that non-linear losses are minimized. Despite the turbulent flow, losses in the screen slots are usually very small, on the range of a few millimeters. Although many slot designs are available, their optimization will thus only lead to marginal improvements of well efficiency. Losses induced by upflow in both screen and casing are only relevant in very deep, corroded or encrusted wells with high pumping rates.

Practical measurements from both the United Kingdom and Germany show that many submersible pumps in water wells operate far from their ideal operating point and thus at efficiencies much lower than possible. This reveals a significant potential for improvement of energy efficiency.

A spreadsheet calculation tool was set up to calculate the losses, flow velocities and Reynolds numbers for all well components (except the pump) for steady-state radial flow in a confined aquifer (for download see Houben et al. 2015b). Losses induced by partial penetration of the well screen were also included and can be significant under certain circumstances. The spreadsheet allows comparing options, e.g. by varying the well geometry and flow rates. It also allows virtual step-drawdown tests, which can be used to dimension wells and obtain their optimum pumping rate. It is currently being expanded to include more options, e.g. wells screened in unconfined aquifers.

CONCLUSIONS

The most important losses measured in a water well occur in the aquifer and the wellbore skin, if present. The prevention or removal of the latter is thus the best option to optimize the well hydraulics. Additionally, hydraulically optimized wells also show less and slower ageing, which makes them more cost-effective. Submersible pumps surprisingly often operate under non-ideal conditions, which also leaves room for energetic optimization, leading to cost saving and extended pump life cycles.

Although the energy gain obtained from the optimization of an individual well may be small, the overall effects can be large, considering the long operational life span of wells and their sheer number.

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SESSION III

UNDERSTANDING PATHWAYS TRANSFERRING NUTRIENTS TO STREAMS — IMPLICATIONS FOR WATER QUALITY MANAGEMENT STRATEGIES

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ABSTRACT

Approximately half of Ireland's water bodies still do not meet the required water quality standards. Management strategies will therefore need to be strategically targeted and prioritised to make the best use of the resources that are likely to be available. As part of the river basin management planning process, assessments are being carried out to determine the significant issues and significant pressures in each water body, as the basis for selecting 'the right measure in the right place'. Excess nutrients leading to eutrophication are the biggest problem, but they arise from different sources, and follow different pathways to get to the receptors. This means that management strategies specific to individual water bodies will be required. Development of a 3D hydrogeological conceptual model is a critical component of the process. Other catchment issues that would benefit from input from the hydrogeological community include the role of geochemistry and hydrogeological conditions in controlling phosphorus and nitrogen transport to streams, and heavy metal concentrations in rivers and lakes.

INTRODUCTION

Despite considerable investment in recent years, approximately half of all Irish water bodies still do not meet Water Framework Directive (WFD; European Parliament and Council, 2000) objectives (DHPCLG, 2017). The greatest challenges lie within the transitional water body category, i.e. our estuaries (Figure 1). There are ambitious industry initiatives in place to develop the agricultural sector in Ireland with Food Harvest 2020 (DAFF, 2011) and Food Wise 2025 (DAFM, 2015), yet significant improvements in water quality still need to be made, even under the existing levels of development.

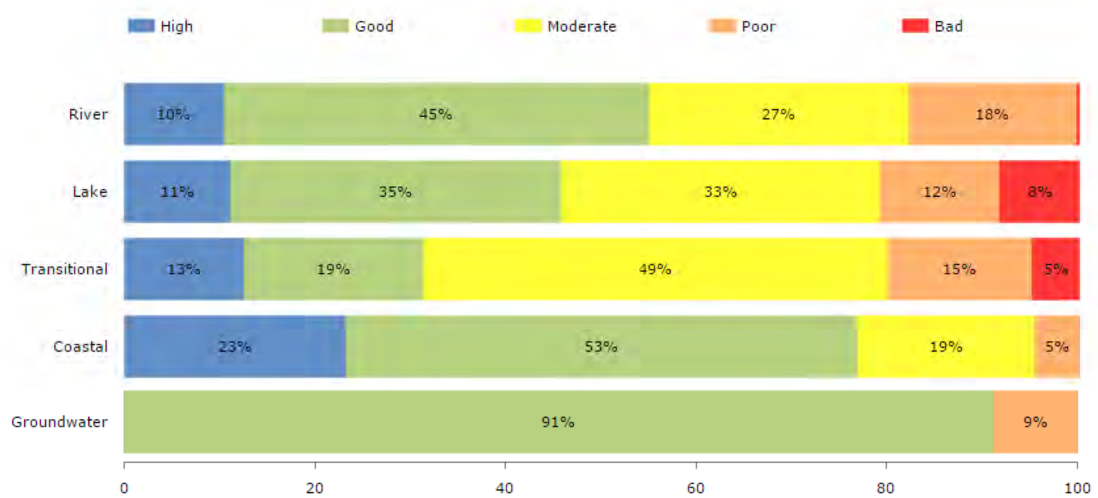

Figure 1. Ireland's water quality status in 2015, as a percentage of monitored water bodies

An intensive assessment process is being conducted by the EPA, with support from RPS consultants, local authorities and other public bodies, to characterise the key issues and pressures causing the problems in waterbodies that are *At Risk* of not meeting their WFD objectives. The key water quality issues in Ireland from the WFD perspective are excess phosphorus in the freshwater environment, excess nitrogen in the marine environment, and excess nitrogen and phosphorus in the estuarine environment, all of which lead to eutrophication. Agriculture is a significant pressure in approximately 60% of *At Risk* rivers and lakes, followed by discharges from urban areas (DHPCLG, 2017). The significant pressures in the estuarine and marine environment are still currently being assessed, but initial indications are that they are a mix of direct discharges from the larger urban areas near the coast, as well as inputs from multiple sources from the upstream catchment areas. While there are localised groundwater drinking water quality issues arising from pathogens and high nitrate, some of which can be related to poor well construction, from the WFD perspective, water quality in our groundwater bodies is relatively good. The key WFD issues are typically being associated with localised contaminated land, and impacts on a small number of groundwater dependent terrestrial ecosystems. Groundwater can also be a pathway however, delivering excess loads of nitrogen and phosphorus to surface waters.

The philosophy in this, the second river basin management planning cycle, is to work towards better understanding the relationships between the sources, pathways and receptors where there are water quality problems, and based on the information that is specific to each water body, to select and implement '*the right measure in the right place*' (Daly et al., 2016).

The characterisation assessments have benefitted from a body of work that has been undertaken in recent years on improving our understanding of the sources of nutrients (e.g. Mockler et al., 2016 and Mockler et al., this conference). The WFD national water quality monitoring network has also provided new insights into the condition of our receptors (EPA, 2012, 2016). Knowledge of the pathways has improved greatly through *The Pathways Project*, a large-scale project funded by the EPA aimed at helping to improve understanding of the pathways delivering flow and nutrients to Irish streams (Archbold et al., 2016). Extensive integrated field and modelling studies were carried out in four hydrogeologically contrasting agricultural study catchments spread across the island of Ireland. The findings of the study were used to develop a catchment characterisation tool (CCT) that is being used by the EPA as part of the suite of characterisation tools (Daly et al., 2016).

This paper reflects on the findings of the *Pathways Project*, and the outcomes of the national characterisation programme, and discusses the important role that geology and hydrogeology have to play in identifying catchment specific management strategies. This paper draws heavily on a recently published paper (Deakin et al, 2016) which the reader is referred to for further details. The two study catchments used in the discussion, the poorly draining Mattock catchment in Co. Meath/Louth which is underlain by a Poor aquifer, and the freely draining Nuenna catchment in Co. Kilkenny which is underlain by a Regionally Important (Rk_d) karst limestone aquifer, were described in a previous IAH conference paper in 2013 (Deakin et al, 2013).

KEY FINDINGS FROM THE NUENNA AND MATTOCK CATCHMENTS

The Nuenna catchment represents the regionally important karst aquifer settings which are present across more than 20% of the country (Fig. 1). The key findings were as follows:

- the groundwater contribution to river discharge was much larger than the near surface contributions;
- nitrate and phosphorus were delivered predominantly via subsurface pathways;
- the most susceptible areas for the delivery of phosphorus to the river were sinking streams that occur in the higher parts of the catchment;

- the most susceptible areas for the delivery of nitrate were the limestone areas overlain by freely-draining soils and subsoils, where infiltration to groundwater was rapid and widespread, and no denitrification was occurring (Orr et al., 2016);
- the most important pollution sources overall were diffuse sources of nutrients across the limestone areas;
- N losses per hectare were 3.5 times higher than in the poorly draining Mattock catchment.

In the Mattock catchment, which represents the poorly productive aquifer settings underlying 73% of the country (Fig. 1):

- the near-surface pathways dominated with the interflow contribution reaching as high as 50% of flow;
- nitrate and phosphorus were transported via the quick overland flow and interflow pathways (Deakin et al., 2014).
- the most susceptible areas for the delivery of phosphorus to the river were poorly drained areas with diffuse agricultural loads and small point sources;
- the most susceptible areas for the delivery of nitrate were in the upper catchment areas where there were relatively small areas of freely-draining soils and subsoils over shallow rock, which contributed proportionally higher nitrate to streams than the rest of the catchment;
- diffuse sources of phosphorus via overland flow were important, as well as widespread small point source discharges (e.g. from septic tank systems and farmyards) being transported via interflow and ditches. These transport mechanisms also explained the pattern of microbial transport throughout the catchment (Flynn et al., 2016);
- P losses per hectare were twice as high compared to the freely-draining Nuenna catchment.

In summary, the contrasting hydrogeological characteristics in the two catchments dictated the nutrient delivery pathways and influenced the ecological outcomes in different ways. If targeted, effective and efficient management strategies are to be identified in each catchment, as is set out as an overarching principle in the draft River Basin Management Plan, the strategies will need to reflect each catchment's respective specific characteristics.

CATCHMENT SPECIFIC MANAGEMENT STRATEGIES – EXAMPLES

In river and lake catchments where nutrients from diffuse pollution are a problem, reduction of the source load is perhaps the most widely considered option for reducing impacts to receptors. However, in poorly draining freshwater environments like the Mattock catchment, where excess phosphorus is the issue, reducing the source load on its own is unlikely to result in sufficient improvements in water quality (Withers et al. 2014; Murphy et al. 2015) because it is the hydrological connections between the source and the receptor, i.e. the pathways, that play the driving role in the transfer of phosphorus to streams (Jordan et al. 2012; Shore et al. 2014; Mellander et al. 2015). Intercepting the phosphorus transport pathways is likely to be a more efficient way of balancing the need to maintain agricultural production while still achieving good water quality targets. Some examples of management strategies for these sorts of poorly-draining environments include edge of field wetlands (Ockenden et al. 2012), buffer strips, or management of ditches (Shore et al. 2015). Re-establishment of wetlands has also been used in Denmark for reducing nitrogen loads to downstream receptors by encouraging denitrification (Hoffmann, C. and Baattrup-Pedersen, 2007). This may mean a change of focus for regulators who, because of the legislative tools available to them, are often more familiar with managing sources.

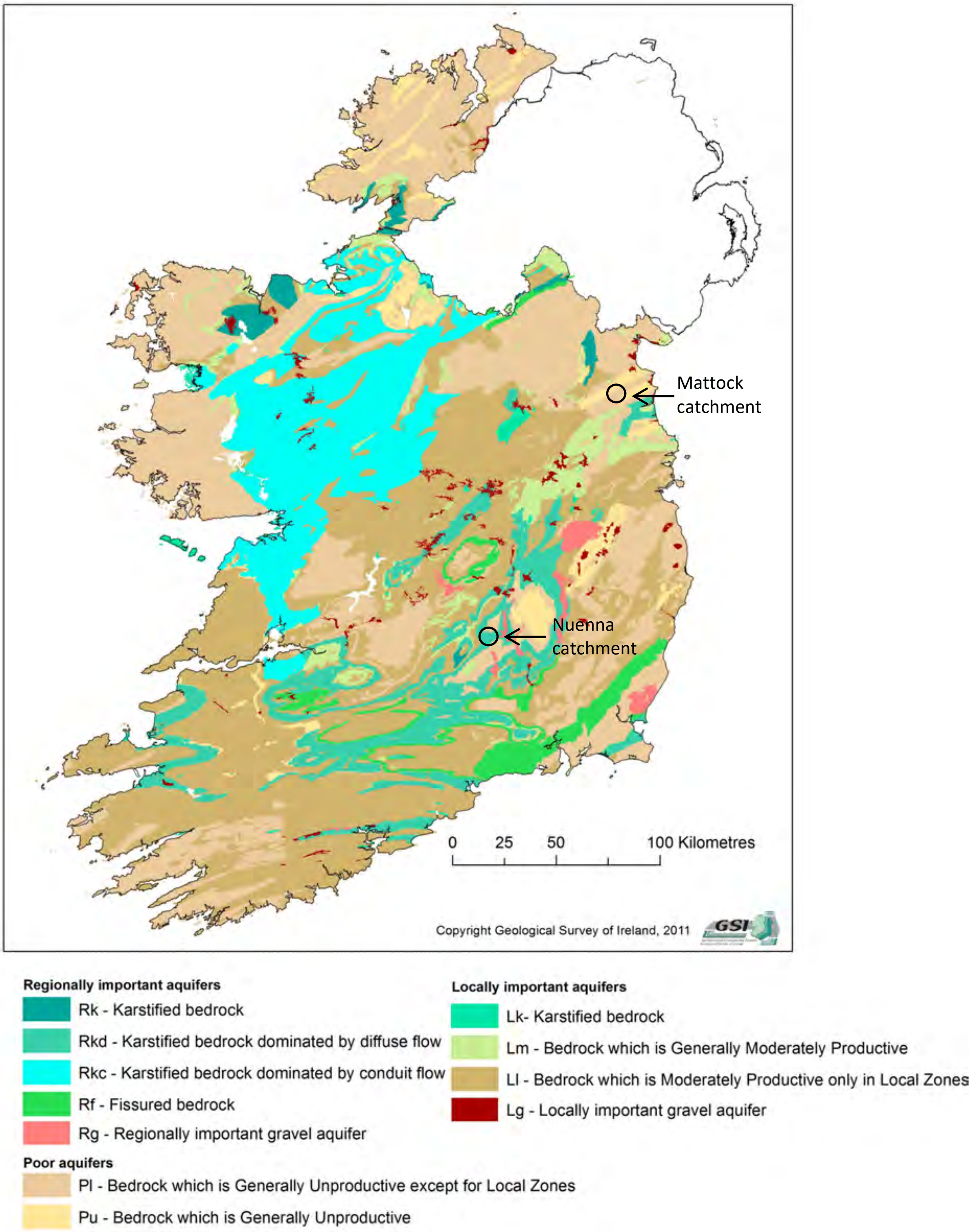

Figure 1. Location of the Mattock and Nuenna catchments in the context of Irish aquifers.

In freely-draining catchments with soils, subsoils and bedrock which are not favourable for denitrification, excess nitrogen leaching is typically the main concern because nitrate is highly mobile. In these settings the installation of riparian buffer strips to intercept fertilizer runoff via overland flow would be ineffective (Mellander et al. 2012; Ibrahim et al. 2013) because the pathway flow is in the vertical direction to groundwater. Breaking the N pathway links between these areas and sensitive receptors is very difficult. In these scenarios, reduction of the source load is likely to be the most efficient option. Source reduction measures include effective nutrient management planning, enforcement of the Good Agricultural Practice Regulations (Government of Ireland 2014), and best management practices such as use of catch crops, clover and optimising the timing of fertiliser applications.

Resolving the catchment-wide issues impacting on the estuarine and marine environments has received comparatively less attention to date than rivers and lakes. Where reduction of nitrogen loads is required, the critical source areas are likely to be areas within the catchment where there is intensive agriculture overlying freely-draining soils, subsoils and productive groundwater aquifers. Whilst the N concentrations in those groundwater bodies might be low when compared against the drinking water standards, and may not impinge on achieving good ecological status in the interconnected river or lake waterbodies, they may nevertheless be very significant in terms of the estuary, and therefore management of the catchment as a whole.

OTHER ISSUES TO RESOLVE

There are a number of other hydrogeological issues that have arisen in the characterisation process that would benefit from input from the hydrogeological community.

1. A recent study by Mellander et al. (2016) found that the iron rich soils and subsoils overlying the Old Red Sandstones in the Timoleague catchment in Cork, were less effective in retaining P in the upper soil layers than other comparable catchments where the soils were rich in aluminium. This resulted in unexpectedly high concentrations of P in groundwater in the iron-rich catchment, which is a concern as the groundwater pathway contributions to the stream were significant. Management of the groundwater and interflow pathways to surface waters may therefore potentially be a higher priority than the management of overland flow in certain settings. The question that arises is whether the dynamics of this process are sufficiently understood, and if so, whether the geochemistry of the bedrock, subsoils and soils is sufficiently well known across the country, to map out the areas where these conditions may arise.

2. A second somewhat similar issue is that in the Cregduff ACP catchment in Co. Mayo, the calcium-rich soils appear to have been much better at retaining phosphorus than other areas (Mellander et al. 2013). In that catchment, 0.5 m of soil and subsoil appeared to be adequate to provide protection for groundwater. The authors suggested that a ‘specific vulnerability’ map for phosphorus could be delineated for the catchment, as a further development to the national intrinsic vulnerability map which is not contaminant-specific. The question then arises is whether this occurs in other karst areas, and if so, whether the delivery of phosphorus to groundwater is mainly via swallow holes rather than from diffuse sources? This would obviously have significant implications for management strategies.

3. It is known that there are geogenic sources of phosphorus in some Irish shaley limestones which will need to be considered in the catchment assessments, as they may give rise to natural background P concentrations in waters that are higher than the ecological standards. For example, in Co. Louth, the average concentration of MRP in a groundwater source overlain by more than 10 m of clayey till was 0.065 mg/l as P (Moe and Gaston 2011), and Misstear et al. (2008) found elevated phosphate concentrations in a confined limestone aquifer in Tydavnet in Co. Monaghan of between 0.01 and 0.31 mg/l as P. Do we have natural background concentrations of phosphorus that can be accounted for in shaley bedrock areas, and from marine sediments such as the Irish Sea Till?

4. Similar issues have arisen in places (e.g. Wexford and Killarney) where heavy metal concentrations in rivers are higher than the ecological standards. The question here is whether natural background concentrations in streams could be mapped, which could (and should) then be taken into consideration in assessing ecological standards.

5. A recent study by Orr et al. (2016) has shown that it is not just the soils that govern denitrification processes in Irish catchments, but the characteristics of the poorly productive bedrock also play a significant role. Can we identify and map areas where this occurs, and can we quantify the likely reduction in nitrate as a result?

CONCLUSIONS

One of the key principles adopted for the river basin management planning process in Ireland moving into the second cycle, is putting 'the right measure in the right place'. Characterising the nature of the hydro(geo)logical pathway linkages, and the nature of that pathway, provides a critical part of the evidence base for selecting the most effective measures. A significant part of the evidence base, which is often lacking in catchment assessments, is an understanding of the role of the three dimensional (3D) geological and hydrogeological framework in the fate and transport of nutrients. Studies often focus only on the upper soil layers and slope, and on temporal changes with rainfall which, while important, only provide part of the story. With their knowledge and skills in this area, hydrogeologists are particularly well placed to contribute to the national debate and to help arrive at solutions.

ACKNOWLEDGEMENTS

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WHAT ARE THE MAIN SOURCES OF NUTRIENT INPUTS TO IRELAND'S AQUATIC ENVIRONMENT?

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ABSTRACT

Where rivers and lakes are impacted by excess nutrients, we need to understand the sources of those nutrients before mitigation measures can be selected. In these areas, modelling can be used in conjunction with knowledge from local authorities and information gained from investigative assessments to identify significant pressures that contribute excessive nutrients to surface waters. Where surface waters are impacted by excess nutrients, understanding the sources of those nutrients is key to the development of effective, targeted mitigation measures. In Ireland, nutrient emissions are the main reason that surface waters are not achieving the required Good Status, as defined by the Water Framework Directive (WFD). A model has been developed in order to predict the sources of nutrients contributing to these emissions and to assess future pressures and the likely effectiveness of targeted mitigation scenarios. This Source Load Apportionment Model (SLAM) supports catchment managers by providing scientifically robust evidence to back-up decision-making in relation to reducing nutrient pollution. The SLAM is a source-oriented model that calculates the nitrogen and phosphorus exported from each sector (e.g. pasture, forestry, wastewater discharges) that contribute to nutrient loads in a river. Model output is presented as maps and tables showing the proportions of nutrient emissions to water attributed to each sector in each sub-catchment. The EPA has incorporated these model results into the multiple lines of evidence used for the WFD characterisation process for Irish catchments.

INTRODUCTION

Nutrient enrichment and eutrophication can negatively impact on freshwater ecosystems, and estuarine and coastal waters. In Europe, agriculture is typically the principal source of nitrogen in water bodies, whereas for phosphorus, households and industries tend to be the dominant contributors (Bøgestrand *et al*., 2005).

Modelling can support catchment management by synthesising large amounts of information in order to focus resources when tackling environmental issues. Nutrient source apportionment modelling is used to estimate the nutrient load from various sectors entering water bodies, following attenuation or treatment. Different modelling approaches are available depending on the required purpose. For example, where high-resolution in-stream monitoring data are available, a load-orientated approach can be used to apportion measured loads to either point or diffuse sources based on temporal patterns typically assuming relatively constant inputs from point sources (e.g. Greene *et al*., 2011). Conversely, source-orientated approaches calculate emissions based on emissions source information. This includes annual reported emissions from point discharges from wastewater and industry, and for diffuse sources, data on stocking densities combined with export coefficients based on the catchments hydrogeological characteristics (e.g. Jordan and Smith 2005; Smith *et al*., 2005). The Source Load Apportionment Model (SLAM) (Mockler *et al*., 2016) takes the latter approach, enabling estimates of the relative contribution of sources of nitrogen (N) and phosphorus (P) to surface waters in catchments without in-stream monitoring data.

The SLAM framework was developed to support the proportional and pragmatic assessment of every sub-catchment in Ireland within the national WFD characterisation process framework (Daly *et al*., 2016). These assessments aimed to determine which of the multitude of potential pressures within a water body are significant, so that measures can be more efficiently and specifically targeted to achieve water quality improvements. The source apportionment results were considered alongside a suite of national datasets, including ecological status and trends in ecological and chemical monitoring data; information on land use, pressures, pathways and sensitivity of receptors; enforcement, audit and inspection information from regulatory agencies; and local, on-the-ground knowledge from the Local Authorities and Fisheries agency staff (Daly *et al*., 2016). This systems-approach is vital for integrated catchment management and effective WFD implementation (Voulvoulis *et al*., 2017).

Due to improvements in nutrient management and regulation, there have been notable reductions in total phosphorus, total ammonia and total nitrogen emissions from many Irish catchments since a peak around the mid-1990s (O'Boyle *et al*., 2016). As regulation of point discharges continues to reduce emissions, other sources of nutrients may start to control water quality in these areas. By developing the SLAM framework, the EPA-funded *CatchmentTools* Project aimed to quantify the sources of phosphorus (P) and nitrogen (N) emissions in Irish rivers in order to support the identification of potential pressures resulting in eutrophication. The SLAM has been used for characterising existing and previous state of the water environment, including;

- Assessing the current sources of nutrient emissions to Irelands water bodies, and
- Evaluating changes in sources of nutrient emissions in recent decades.

The SLAM framework also provides capabilities for scenario analyses to support integrated catchment management in Ireland, including:

- Local-scale scenario analyses to identify potential nutrient reduction options to achieve Good Status in nutrient impacted water bodies, and
- Regional-scale scenario analyses to assess the impact of future projections of land cover and land use change, population increases and wastewater treatment improvements.

This paper briefly outlines the models and data, provides an example of the model results, and identifies further areas for development.

DATA AND MODELS

THE SOURCE LOAD APPORTIONMENT MODEL (SLAM) FRAMEWORK

The SLAM Framework incorporates multiple national spatial datasets relating to nutrient emissions to surface water, including land use and physical characteristics of the sub-catchments. Separate modules were developed for each type of nutrient source to facilitate upgrading and comparisons with new data or methods (Figure 1). For example, two of the original modules have already been upgraded with output from more advanced export-coefficient based models in the current version of the framework (v 2.05). The agriculture (pasture & arable) and septic tank systems modules use spatial outputs from the Catchment Characterisation Tool (CCT) (Archbold *et al*,. 2016) and SANICOSE models (Gill and Mockler 2016), respectively. Further details of the model development and application are available in Mockler *et al*., (2016), and the framework structure and user interface are described in Mockler (2016).

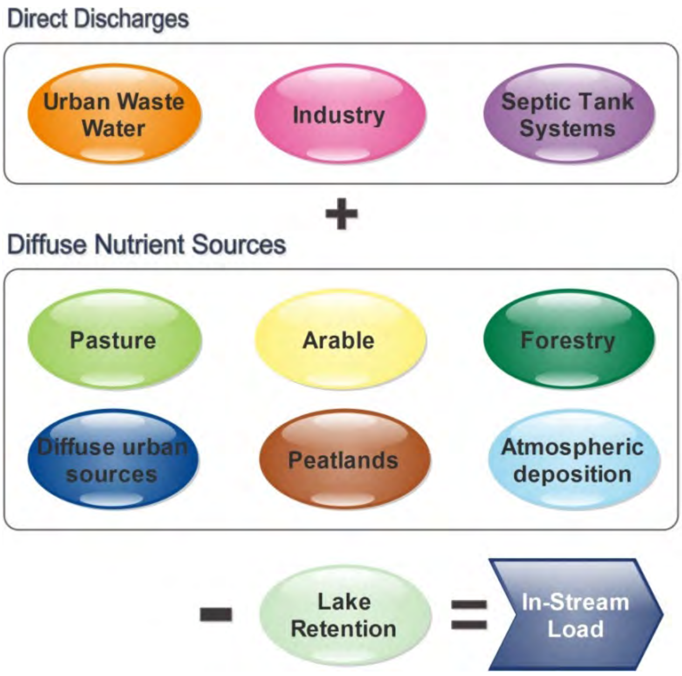

Figure 1. Sub-models of the Source Load Apportionment Model (SLAM) Framework.

The key input dataset for the agriculture module (i.e. the CCT) was the Land-Parcel Identification System (LPIS) which was combined with land management data from the Department of Agriculture, Food and the Marine (DAFM). The 2012 CORINE (Lydon and Smith, 2014) land cover data were used in the forestry, peatlands and urban sub-models. Various export coefficients were then applied in each of the modules to estimate their annual nutrient emissions to water. Loads from direct discharges were calculated from data collected by the EPA, including Annual Environmental Reports, the EPA Licensing Enforcement and Monitoring Application (LEMA), and the Pollutant Release and Transfer Register (PRTR) database.

RESULTS

LOAD APPORTIONMENT BY SECTOR: SUIR CATCHMENT

The SLAM results for the Suir catchment showed that pasture was the dominant source of nitrogen (78%), whereas pasture and wastewater discharges were equally dominant sources of phosphorus (35% each). The total catchment TP loads were biased by the large contribution from the Waterford agglomeration (33 t yr-1 TP) at the mouth of the catchment, which is equivalent to 26% of the total estimated TP losses. Within the Suir catchment, there were large variations in the percentage contributions from direct discharges for phosphorus between sub-catchments (Figure 2). These ranged from 1% to 90% and reflect the population distribution in the catchment.

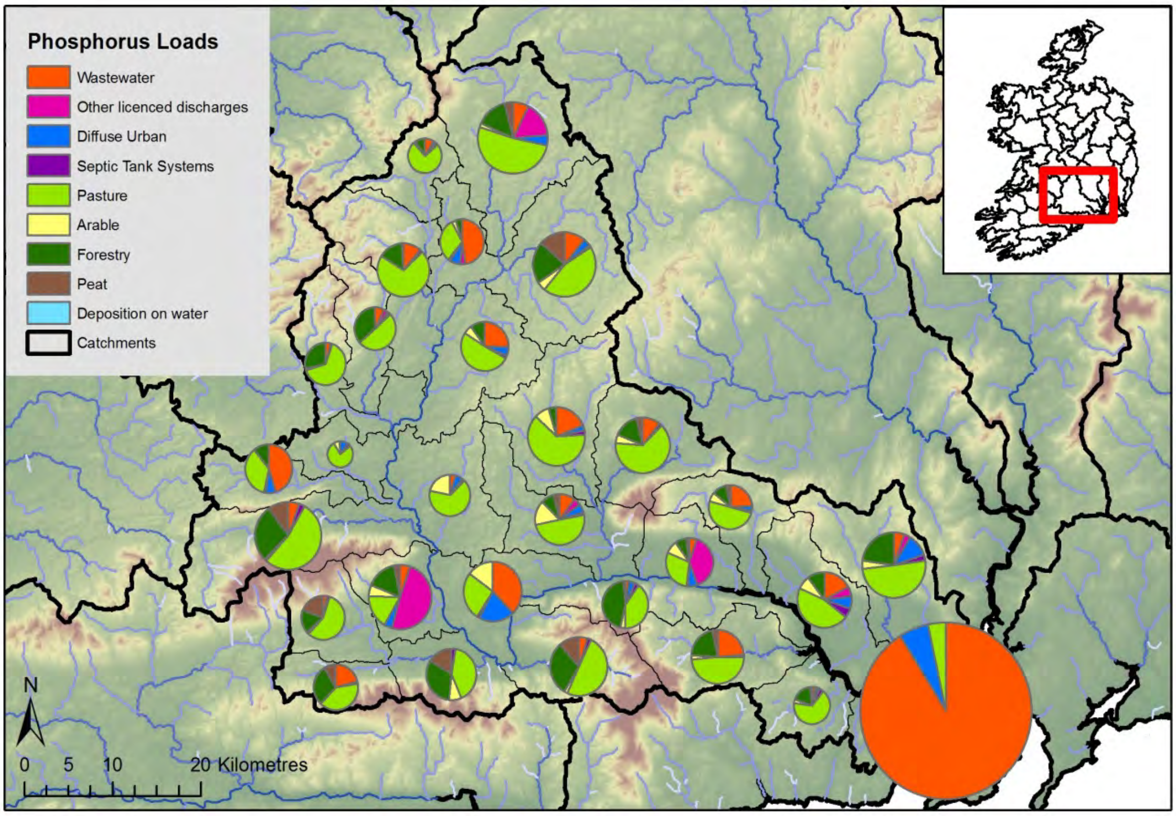

Figure 2. Phosphorus load apportionment results for the Suir catchment (size of pie indicates relative contribution of annual loads from each sub-catchment).

WHAT AND WHERE? NUTRIENTS AT NATIONAL LEVEL

The SLAM results were compared with monitoring data for 16 major river catchments covering 50% of the area of Ireland to assess the model performance prior to its extension to cover the entire country (Mockler *et al*., submitted). These data included three years (2012 - 2014) of annual nutrient loads, calculated from flow and nutrient concentration data collected by the EPA (see O'Boyle *et al*., 2016).

At national level, agriculture was the dominant source of N, whereas the dominant sources of P emissions varied by land use and hydrogeological setting. Further analyses with catchment characteristics confirmed that P emissions from pasture were mainly driven by hydrogeological conditions, not the magnitude of the pressure. This emphasises that phosphorus mitigation options should aim to interrupt the local source-pathway-receptor relationships.

The national load apportionment results can be used in conjunction with the WFD risk assessments to assess hot-spots for each sector. This can be used for desk-based assessments prior to, for example, detailed investigations or selection of study catchments. Figure 3 presents the estimated contributions from septic tank systems to the total annual P and N load emissions to surface waters. This information can be used to target areas that have a relatively high number of these systems in high-susceptibility settings.

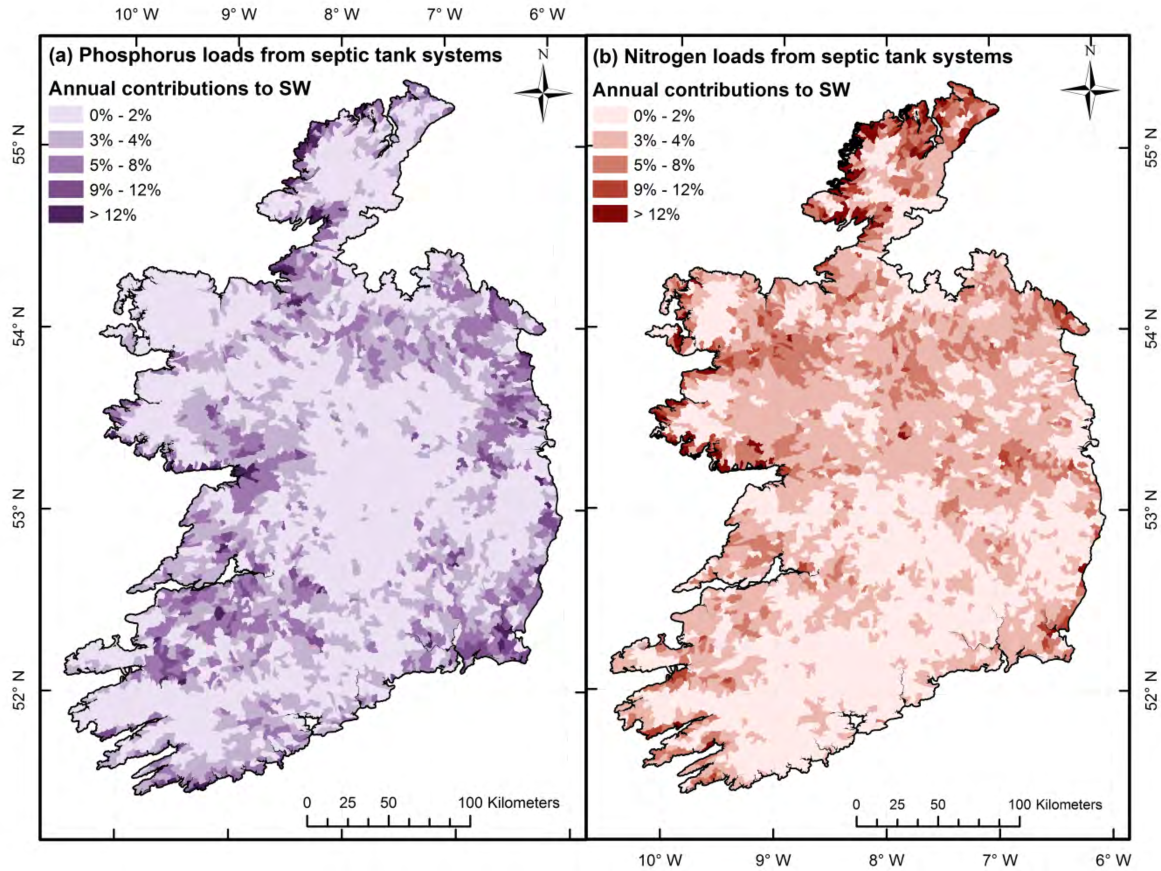

Figure 3. Modelled contribution of septic tank systems to total annual loads of (a) phosphorus and (b) nitrogen to surface water bodies in Ireland.

DISCUSSION

THE IMPORTANCE OF HYDROGEOLOGY FOR NUTRIENT MODELLING

Water mobilises and transports nutrients through the landscape and the attenuation potential varies considerably with hydrological and hydrogeological settings, and type of nutrient (Archbold *et al*., 2016). For instance, nitrate is typically delivered to streams via subsurface pathways (Kröger *et a*l., 2007; Tesoriero *et al*., 2009). The majority of phosphorus from diffuse sources is driven by storm events and delivered via overland flow (Jordan et al. 2005), although significant quantities may also be delivered via tile drainage (Monaghan et al. 2016; Zimmer *et al*., 2016) and groundwater pathways (Mellander *et al*., 2016) with individual hot-spots of nutrient loss, or critical source areas, contributing a relatively high proportion of the nutrients exported from the landscape (Pionke e*t al*., 2000).

As hydrology is a key driver of nutrient delivery at catchment scale, hydrogeological processes should be incorporated in models. For the spatial modelling approach used in this study, simplified conceptual flow paths were included in the models of emissions from agricultural and septic tank systems. The multiple complexities were reduced to two main pathways; 1) near surface including overland flow and flow through soils and subsoils, and 2) a (deep) groundwater pathway. This conceptualisation will evolve as further research explores national mapping of flow paths through Irish landscapes including, for example, the on-going GSI transition zone research project.

TIMING OF NUTRIENT EMISSIONS

The complex temporal variations of nutrient emissions are often essential to assessing impacts on ecology. This fourth dimension is not represented in the SLAM results, and can be essential for certain assessments. For example, the annual percentage contribution of loads from septic tank systems may be small overall at the sub-catchment scale, but their impact in small stream headwaters can be significant during low flow periods (Withers *et al*., 2012).

In contrast to dynamic models that produce temporal analyses, the SLAM approach allows the model to be applied throughout Ireland, independently of the availability of measured in-stream calibration data. Development, however, is on-going in collaboration with the *ESManage* Project to couple the SLAM with an existing dynamic water quality model, the Catchment Modelling Tool (Mockler *et al*., 2014) to produce an ecosystems services modelling framework. This dynamic model supports the investigation of temporal variations in river nutrient concentrations.

HOW TO CONTRIBUTE TO THE FRAMEWORK

This study aimed to incorporate the best available national research and data to estimate and apportion the sources of nitrogen and phosphorus in Irish surface waters. However, due to limited resources of the project, some of the models are still based on simple emission factors. For example, there is a growing body of research on nutrient emissions from forestry and peatlands that has not yet been interpreted into a national sector model. As our understanding of land cover, land use and hydrogeological connections grows, research findings can be incorporated into the SLAM Framework. Hence, where feasible, it is recommended that future related research projects attempt to extrapolate sector-specific data to produce national spatial estimates of nutrient emissions that can be incorporated into the SLAM framework.

CONCLUSIONS

The SLAM results have been analysed at a range of scales and coupled with other models in order to improve understanding of catchment dynamics. For example, the dynamic nature of anthropogenic pressures at catchment scale were examined using loading information spanning over a decade to explore the resulting impacts on Irish estuaries (Ní Longphuirt *et al., 2016).* At local scale, Mockler *et al*., (2016) illustrated a simple assessment of potential mitigation measures in a nutrient-enriched water body. The upgrading of the SLAM Framework with new models and data will continue in order to support integrated catchment management in Ireland.

Incorporating the SLAM results into Irish catchment science assessments has facilitated assessment of nutrient load information in a logical, structured, consistent and comparative way across the country and has therefore provided robust assessment of the information. The results however, are only one of the ‘tools in the toolbox’ to determine the significant pressures. The SLAM results should be used in combination with other information, as nutrient load does not necessarily mean impact. The design of measures requires integrating hydro-science and social-science assessments to ensure decision makers have the best information when evaluating cost efficiency and effectiveness (Psaltopoulos et al. 2017), and models such as the SLAM provide some of the necessary information to feed into these assessments.

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THE INFLUENCE OF HYDROGEOLOGICAL SETTING ON NITRATE FATE AND TRANSPORT IN IRISH AND BRITISH AQUIFERS AND THE IMPLICATIONS FOR CATCHMENT MANAGEMENT

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ABSTRACT

Excess nitrate (NO_3) in groundwater is a significant problem in both Ireland and Britain. This paper presents findings from an Irish study and a British study which both investigate fate and transport of nitrate in groundwater.

The British study, carried out for a water company, quantified the sources and investigated the transport of nitrate in three catchments in rural and semi-urban settings underlain by chalk or sandstone bedrock. The Irish study investigated the influence of hydrogeological setting on nitrate fate in agricultural catchments underlain by bedrock aquifers with contrasting hydrogeological properties.

Both the British and Irish studies highlighted the importance of considering the hydrogeological setting for groundwater quality monitoring and the implementation of contamination mitigation measures. The study in the British catchments highlighted the dominance of agricultural sources of nitrate in both rural and semi-urban settings, the significant lag time for nitrate to reach the abstraction points once applied to the surface, and the implications this has on catchment management interventions. Investigations in the Irish catchments showed that in karstified aquifers nitrate management strategies should focus on the deep groundwater pathways, whereas in catchments underlain by lower permeability aquifers, the focus should be on shallower pathways. Significantly, the study also showed denitrification is occurring in the lower permeability bedrock aquifer. Incorporating these considerations when developing catchment management plans can assist in addressing the impact of agricultural practices on the groundwater quality, reduce long-term costs associated with water treatment and contribute towards achieving the aims of the Water Framework Directive.

INTRODUCTION

Excess nitrate (NO_3) is a global environmental problem which is expected to worsen as a result of factors linked to the increase in human population and the development of growing economies (Erisman et al. 2011). Identifying the sources of nitrate and characterising catchment-scale processes controlling nitrate fate in groundwater is a fundamental consideration when applying interventions to reduce risks posed to water quality.

This paper presents findings from two separate studies. Both studies include catchments which are set in agricultural setting and are associated with groundwater nitrate contamination. The first study was carried out in the UK for Yorkshire Water to investigate the sources of nitrate in rural and semi-urban catchments. The study aimed to inform better focused and more effective actions to reduce nitrate inputs and ultimately to reverse rising trends of nitrate in groundwater abstractions from these aquifers.

The second study was carried out in Ireland to investigate the influence of hydrogeological setting on nitrate fate in Irish agricultural catchments. The study used a field based approach to characterise the dominant processes influencing nitrogen fate in groundwater in catchments underlain by bedrock aquifers with contrasting hydrogeological properties, but having comparable nutrient loads. Findings from this research are presented in Orr et al. (2016) and in the Irish Groundwater Newsletter Issue 54 (2016).

NITRATE SOURCES AND TRANSPORT IN BRITISH DUAL POROSITY AQUIFERS

Nitrate concentrations in the unconfined aquifers of Yorkshire have been rising over several decades and many of the public supply sources used by Yorkshire Water now exceed the European Union Drinking Water Directive (98/83/EC) limit of 50 mg/l NO_3 (Figure 1).

Yorkshire Water have always achieved compliance with the Drinking Water Directive through treatment and/or blending. Treatment can be an effective way of removing nitrate but comes with high environmental and economic costs. Treatment plants have short asset lives, require large amounts of power and chemicals and the waste produced can be difficult to dispose of. Capital costs of a nitrate removal plant are approximately £0.5M per Ml/d and subsequent operational costs are typically £5 per kg of N removed. Therefore, catchment management can be both environmentally and economically advantageous compared to conventional treatment technologies or blending, resulting in a more sustainable approach to the problem.

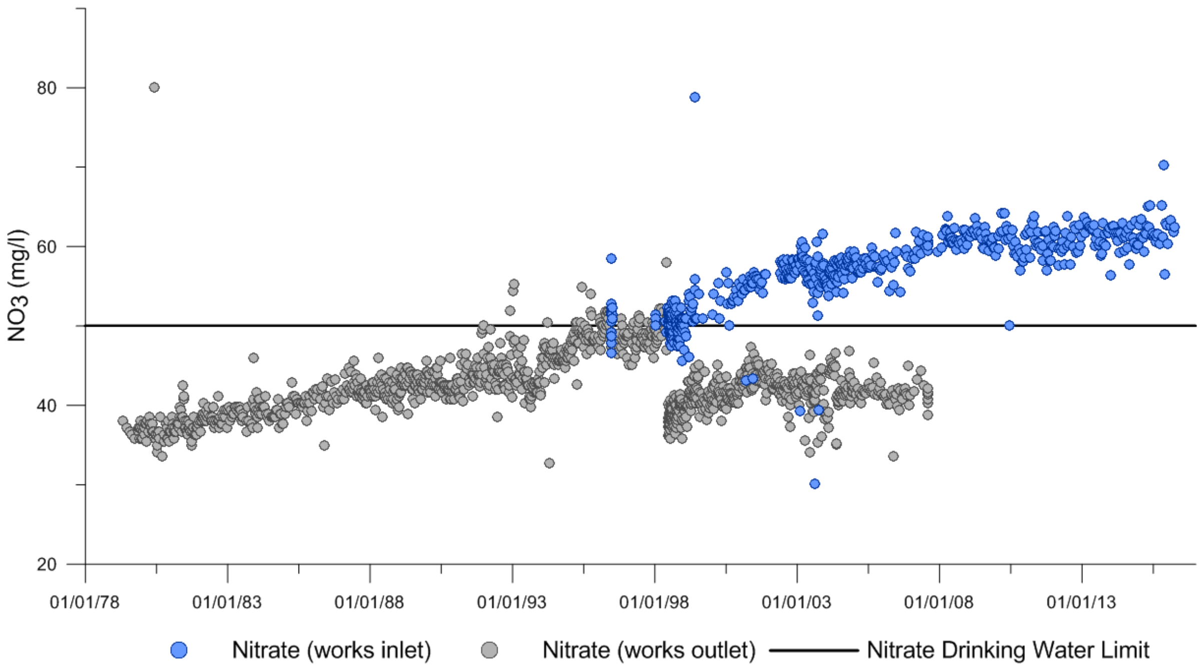

Figure 1 Nitrate concentrations at the works inlet and works outlet at the Kilham abstraction, 1979-2016. The reduction in nitrate concentrations in the works outlet in 1998 was in response to the installation of a treatment works.

Yorkshire Water have highlighted the need to understand the source of nitrate in the raw water abstracted for public water supply to provide a balanced, scientifically robust account of the contributions from non-agricultural and agricultural activities. This improved understanding of the source of nitrate will help inform water resource managers and farmers on effective catchment management solutions and inform decisions on where, when and how catchment management might reduce the rising trends of nitrate concentrations.

The Yorkshire Water abstractions are located in the Yorkshire Chalk and Triassic Sherwood Sandstone which are principle aquifers of regional importance. In both aquifers recharges is controlled by the presence of low permeability quaternary deposits. The Yorkshire Chalk is highly heterogeneous as a result of dissolution and karstic development. In the Sherwood Sandstone fissure flow is an important source of improved yields as it drains the inter-granular storage. Permeability layering related to grain size is evident within the sandstone where the coarser grained units transmit more groundwater.

This study has three research and development themes:

1. Source Apportionment (the focus of this study), which aims to gain an understanding of the sources of nitrate and to understand the magnitude of nitrate leaching to groundwater. This will allow better focused and more effective actions to reduce nitrate inputs and ultimately to reverse rising trends and reduce nitrate concentrations.
2. Nitrate Storage Transport and Pathways, which aims to improve the characterisation and understanding of the geology and hydrogeology of the catchments with particular focus on characterising the role of soil and superficial geological deposits and infiltration and recharge mechanisms in controlling nitrate levels in underlying groundwater. This will inform the mechanisms by which the nitrate is transported from the sources to the groundwater abstractions, which are the receptors.
3. Integrated Catchment Management, which aims to identify the appropriate and applicable catchment management approach and intervention measures available based on the findings from R&D theme 1 and 2. The interventions aim to reduce the leaching of nitrate from agricultural land to the underlying groundwater body and ultimately into the Yorkshire Water public water supply abstractions.

PILOT CATCHMENTS

Three pilot study catchments were identified as characterising different settings typical of Yorkshire. The three pilot catchments are:

- Kilham: Yorkshire Chalk bedrock aquifer mostly overlain by thin and/or permeable quaternary deposits and located within a rural setting,
- Pollington and Heck: Sherwood Sandstone bedrock aquifer, which is overlain by both areas of thin and/or permeable quaternary deposits and areas of low permeability quaternary deposits. This catchment is located within a rural setting, and
- Armthorpe: Sherwood Sandstone bedrock aquifer, overlain by made ground in urban areas or in the rural areas of both thin and/or permeable quaternary deposits and low permeability quaternary deposits. Armthorpe was chosen specifically because it is located within a semi-urban setting.

The study identified and quantified the sources of nitrate in each catchment. Sources of nitrate considered included agriculture, sewage sludge spreading, leaking sewers, septic tanks, mains water, urban land uses, landfills, cemeteries, pollution incidents, licenced discharges to groundwater and precipitation.

Agricultural land use was determined from Agricultural Census data (produced by EDINA at Edinburgh University Data Library and the Department of Environment, Food and Rural Affairs (DEFRA) for England) and field scale land use data (CEH Land Cover® plus (LC+) Crops). Nitrogen loading rates from each land use were calculated using the Department for Environment Food and Rural Affairs (DEFRA) Fertiliser Manual (RB209) which details recommendations for calculating fertiliser application rates to crops and grassland. The rate of N leaching below the root zone was calculated for each crop type using the Farmscoper decision support tool. It is an open access tool developed by ADAS Ltd to assess agricultural pollution loads and the impacts of farm mitigation measures on pollution loads.

The Catchment Nitrogen and Phosphorus Loading to Groundwater spreadsheet developed by Entec UK Ltd (2010) was used to calculate the rate of N leaching from non-agricultural sources.

NITRATE SOURCES AND TRANSPORT

Based on the nitrate leaching analysis of each identified potential source, the study found that the main source of nitrate in all three catchments is agriculture. In the rural catchments of Kiham and Heck and Pollington agriculture accounted for >88% of the nitrate leaching to groundwater. In these catchments the remaining nitrate leaching to groundwater was from landfills, septic tanks, precipitation and leaking mains water and sewers. In the semi-urban Armthorpe catchment agriculture accounted for 67% of the nitrate leaching to groundwater. Leaking sewers and landfills also accounted for considerable proportions of nitrate leaching to the groundwater. Other urban sources which contribute nitrate leaching to groundwater in the Armthorpe catchment include leaking mains water, septic tanks and urban parks and recreational areas including golf courses and sports playing fields.

Nitrate concentrations in the abstraction boreholes indicate that the abstraction rate can have an influence on the nitrate concentrations, as higher abstraction rates increase the volume of higher nitrate groundwater entering the boreholes. It is likely that this is due to the increase in the cone of depression resulting in an increase in flow from shallower depths of the aquifer which contain younger higher nitrate waters. Furthermore, boreholes with deeper abstraction zones are associated with lower nitrate concentrations. This indicates a decrease in groundwater nitrate concentrations with depth and therefore abstracting from greater depths yields lower nitrate water.

The study found that while there has generally been a decrease in nitrate leaching to groundwater from agricultural sources since the 1980s, there has been an increase in groundwater nitrate concentrations. The increase in nitrate is likely to be as a result of high nitrate storage in the unsaturated zone and this highlights the potential influence of time lag associated with any proposed intervention implemented in the catchments.

NITRATE FATE AND TRANSPORT IN IRISH FRACTURED AQUIFERS

The study in Ireland used a field-based approach to characterise the dominant processes influencing nitrogen concentrations in groundwater in two rural Irish catchments underlain by bedrock aquifers with contrasting (physical and geochemical) hydrogeological properties, but having comparable nutrient loads (approximately 400 kg N/ha/yr) and thin to no subsoil cover over much of their area.

This research examined the spatial heterogeneity of biogeochemical processes across each catchment and with depth. This was achieved through monitoring well tracer tests and the analysis of chemical and isotopic signatures of groundwater and surface water.

The research focused on two catchments; the Nuenna Catchment which is a well-drained catchment underlain by a regionally productive diffuse karst (Rk_d) pure bedded limestone aquifer, and the Glen Burn Catchment which is a poorly drained catchment underlain by a poorly productive (Pl) Silurian greywacke aquifer. While both aquifers are fractured, transmissivity ranges determined from pumping tests at well clusters are much greater in the Nuenna compared to the Glen Burn.

NUENNA

Groundwater transport of nitrate in the Nuenna Catchment is dominated by fracture flow in the deep groundwater where nitrate concentrations are higher than in the shallow groundwater (Figure 2). Relatively little change in NO_3/Cl ratios or nitrate isotopic signature with depth suggest good mixing in the deeper part of the aquifer and that biogeochemical reactions are not a significant factor influencing nitrate fate once the nitrate enters the deeper bedrock (Figure 2).

Nitrification is the dominant biogeochemical process influencing N fate in the aquifer. Hydrochemical and isotopic findings suggest that widespread denitrification is unlikely across the Nuenna Catchment but localised partial nitrification may be intermittently occurring in the shallow groundwater with limited impact on catchment surface water quality (Figures 2 and 3).

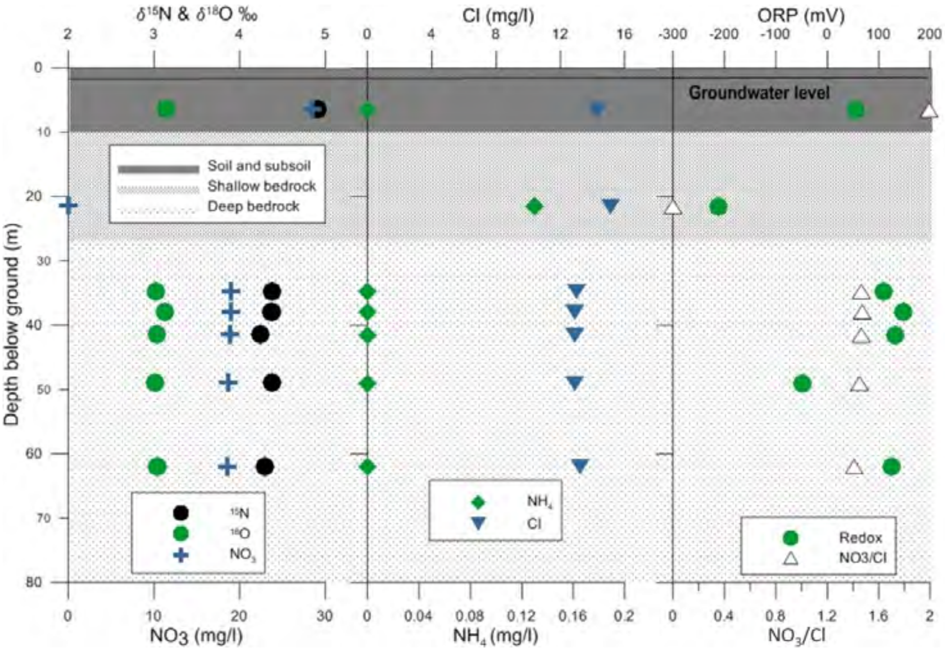

Figure 2 Variation of NO_3, NH_4, Cl, ORP concentrations and NO_3 isotope ($\delta^{15}N$ and $\delta^{18}O$) values with depth in the NU2 cluster, sampled using a packer system and low flow pump, Nuenna Catchment, Co. Kilkenny.

GLEN BURN

In the Glen Burn catchment investigations show that the shallow groundwater is the dominant groundwater pathway for delivering nitrate to aquatic receptors. Water quality and isotopic analyses show that denitrification is likely to be occurring in the bedrock resulting in lower nitrate concentrations with depth (Figures 3 and 4). Water quality data suggest that both autotrophic and heterotrophic denitrification occurs, yet varies spatially across the site according to available electron donors.

Nitrate concentration decreases with depth in the Glen Burn aquifer, which also corresponds to a reduction in the NO_3/Cl ratio (Figure 4). A decrease in NO_3/Cl ratio may indicate dilution from older water. However considering the reduction in oxidation reduction potential (ORP) this would indicate suitable denitrifying conditions. This is supported by the significant enrichment of both $\delta^{15}N$ and $\delta^{18}O$ which indicates denitrification in the bedrock groundwater. More enriched nitrate isotopic values in the deep groundwater compared to the shallow groundwater suggest that nitrate removal through denitrification continues at depth as it infiltrates downwards. This is supported by a general trend across the groundwater samples showing lower groundwater nitrate concentrations contain more enriched $\delta^{15}N$. Significantly, these values display an enrichment ratio of 1.7 between $\delta^{15}N$ and $\delta^{18}O$

(Figure 3) which is within the enrichment ratio range of between 1.3 and 2.1 attributed to denitrification (Böttcher et al. 1990; Aravena & Robertson 1998; Fukada et al. 2003)

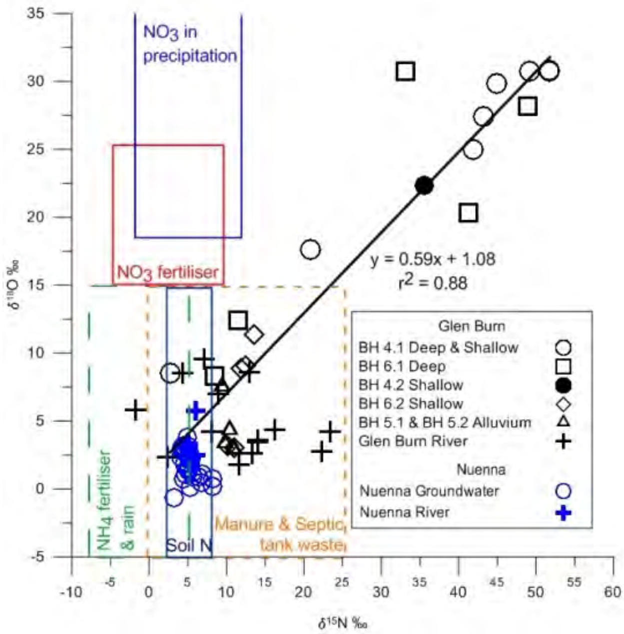

Figure 3 $\delta^{15}N$ and $\delta^{18}O$ in groundwater and surface water in the Glen Burn Catchment, Co. Down. Boxes show the range of $\delta^{15}N$ for manure and septic tank waste, NH_4 fertiliser and soil N, adapted from Kendall (1998).

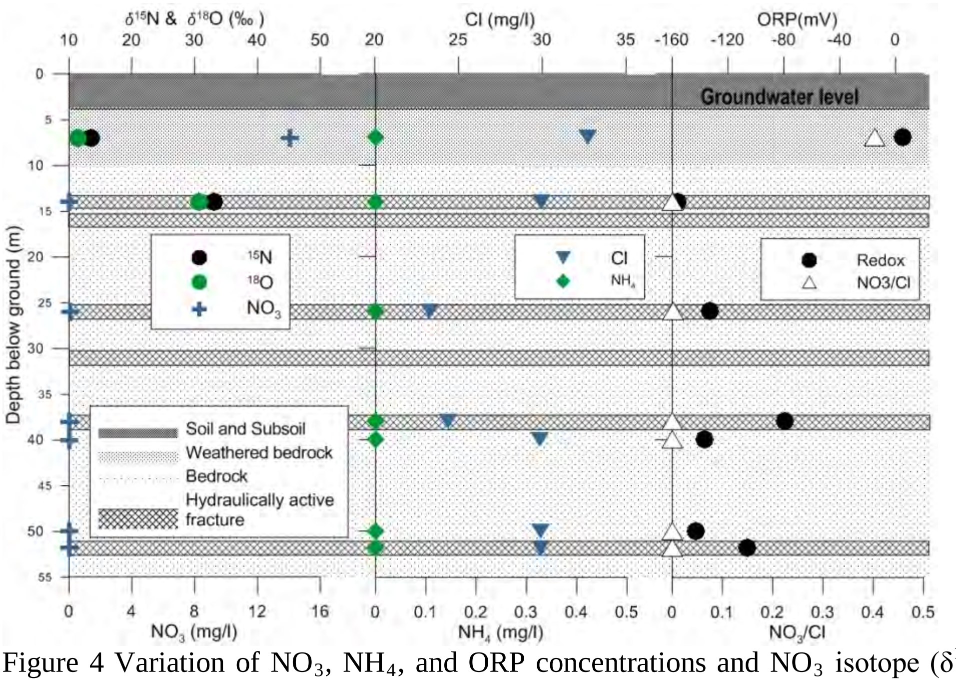

Figure 4 Variation of NO_3, NH_4, and ORP concentrations and NO_3 isotope ($\delta^{15}N$ and $\delta^{18}O$) values with depth in BH6 cluster, sampled using a packer system and low flow pump, Glen Burn, Co. Down.

The findings show that groundwater quality in both the Nuenna and Glen Burn catchments is impacted by contamination. However, the contrasting hydrogeological settings have a significant influence on the dominant biogeochemical processes influencing nitrate fate and transport. The bedrock in both catchments transports groundwater predominantly through fracture flow. However the variation in groundwater discharge via hydraulically active fracture sets with depth and the transmissivity ranges differ considerably in the two catchments investigated. This has considerable influence on the fate and transport of nitrate in the groundwater bodies.

CONCLUSIONS

Both studies highlight the importance of considering the hydrogeological setting for groundwater quality monitoring and the implementation of contamination mitigation measures in catchments. The study in the British catchments highlights the dominance of agricultural sources of nitrate, the lag time for nitrate to reach the abstractions once applied to the surface and the implications this has on catchment management interventions. The study in the Irish catchments shows that in karstified aquifers nitrate management strategies should focus on the role played by deep groundwater pathways and diffuse nitrogen sources, whereas in catchments underlain by lower permeability aquifers, the deep groundwater will be a less significant pathway for nitrate and the focus of such management plans should be on pathways nearer the ground surface. Furthermore, denitrification is evident in the lower permeability bedrock aquifer. Incorporating these considerations when developing catchment management plans can assist in addressing the impact of agricultural practices on the water quality of groundwater bodies and contribute toward achieving the aims of the Water Framework Directive.

ACKNOWLEDGEMENTS

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THE APPLICATION OF QUANTITATIVE TRACER TECHNIQUES TO ASSESS DIFFUSE METAL CONTAMINATION FROM THE FORMER AVOCA MINE SITE: A CASE STUDY OF THE AVOCA RIVER

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(Exploration & Mining Division, Department of Communications, Climate Action and Environment)

ABSTRACT

Mineral extraction at Avoca, Co. Wicklow, over a 250 year period has left an environmental legacy comprising open pits, spoil piles and multiple-level underground mine workings which continue to impact water quality in the Avoca River. Both direct and diffuse acid mine drainage (AMD) contribute a dissolved metal load to the river. To determine the role and extent of the diffuse contribution from the mine site, a quantitative tracer study was undertaken on behalf of the Exploration and Mining Division of the Department of Communications, Climate Action and Environment to assess the mass loading and balance of dissolved metals in the Avoca River, supplementing findings from previous investigations. Eleven tracer tests were undertaken during low-flow conditions on selected river segments within a 2 km stretch of river. Three GGUN-FL30 fluorometers provided by Geological Survey Ireland were employed to continuously record Fluorescein and/or Rhodamine WT concentrations downstream of the dye injection site. The metals loading from diffuse sources, including groundwater, accounted for over 25% of the total zinc load in the upper reaches of the river and over 50% in the lower reaches. Results indicate that diffuse loads alone cause exceedance of environmental quality standards in the Avoca River at several locations adjacent to and downstream of the mining areas. The new information will be important in the determination of cost-effective remediation strategies.

INTRODUCTION

The Avoca mining area is located in the eastern foothills of the Wicklow Mountains, some 55 kilometres south of Dublin. As shown in Figure 1, the East and West Avoca Mining areas are separated by the Avoca River which is formed at the "Meeting of the Waters" by the confluence of the Avonbeg and Avonmore Rivers, approximately 1.5 km north of the mining areas. Prior to closure in 1982, the mine site was worked intermittently for approximately 250 years with the extraction of 16 Mt of copper and pyrite and on-site processing to produce concentrates. Mineral extraction left an environmental legacy comprised of open pits, spoil piles, shafts and adits which continue to impact the water quality of the Avoca River through point and diffuse source contamination.

Acid mine drainage (AMD) from East and West Avoca contributes both direct and diffuse dissolved metal loads to the river. Direct AMD originates either as surface water or groundwater prior to being hydraulically captured by the underground mine workings and discharged to the river through mine adits as point sources. Diffuse groundwater flow also contributes a contaminant load to the river. Infiltration and lateral groundwater flow through the spoil materials results in acid generation and chemical leaching of metals from the spoils, most notably, within the alluvial aquifer where groundwater is in direct contact with the metal laden spoil areas on both sides of the river. Quantifying the extent of direct or point and diffuse contamination provides valuable information regarding contaminant fate and transport at the site.

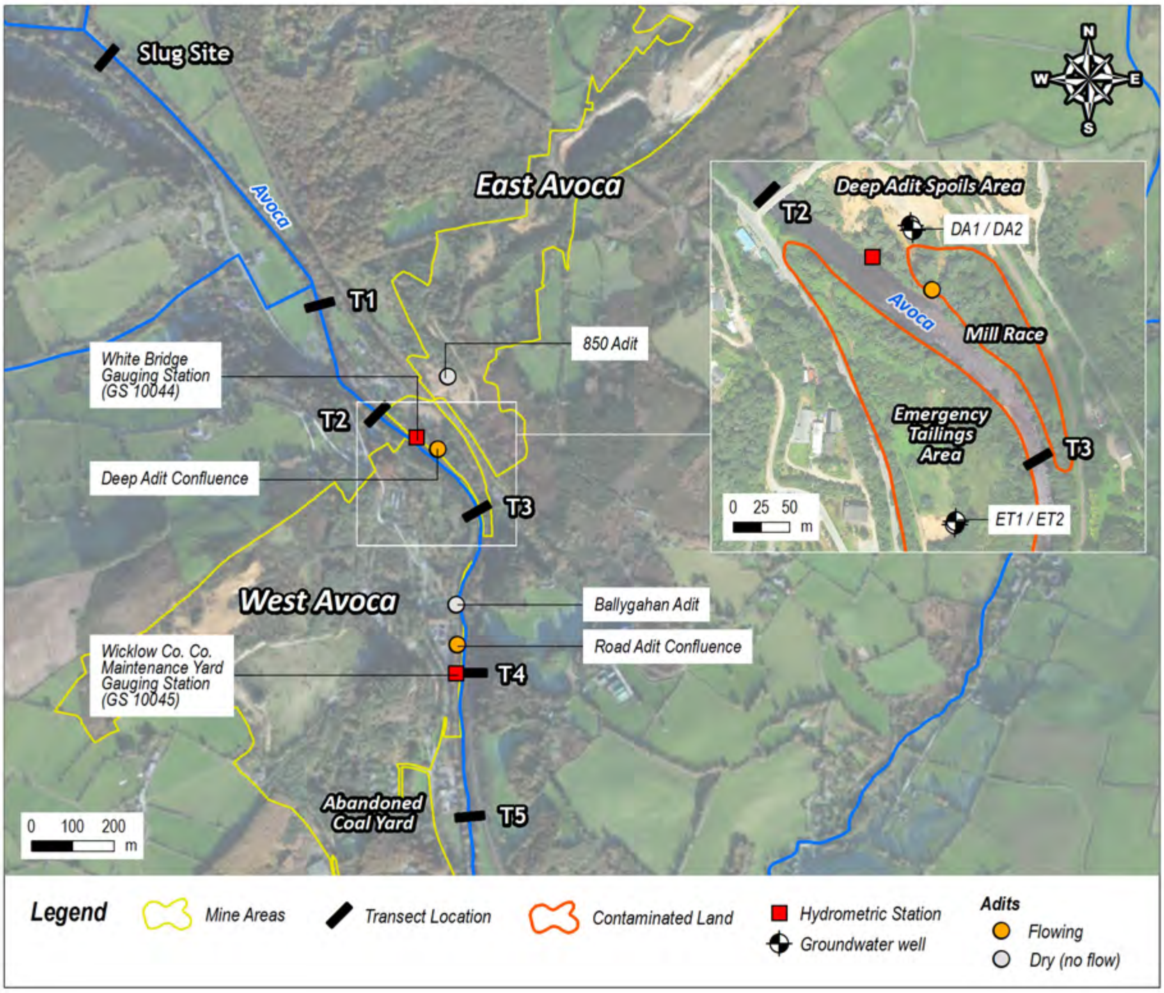

Figure 1 Avoca mining area and tracer study design

Determining if diffuse contamination would result in the exceedance of water quality standards in a potential future scenario whereby, point sources of contamination are captured and treated, is an important step in guiding future remediation strategies. As part of an ongoing monitoring programme at the former mine site on behalf of the Exploration and Mining Division of the Department of Communications, Climate Action and Environment, CDM Smith completed a programme of tracer tests on the Avoca River in September 2016. Findings from these tests supplement a previous tracer study undertaken in September 2007 as part of a feasibility study for the management and remediation of the Avoca Mining Site (CDM, 2008). This was a one-time study and additional tracer tests during low flow conditions (when diffuse flow impacts are greatest) were necessary.

The 2007 tracer study identified river segments which were gaining or losing flow within a 2 km stretch. Sodium chloride was employed as a tracer with specific conductivity sensors installed to continuously monitor chloride concentrations at five transects downstream of the chloride addition location ("slug site" in Figure 1). Mass balance analysis indicated a continuous increase in dissolved metal loads from upstream of the mining areas to downstream. In the upper reaches of the river, diffuse loads of dissolved zinc, copper and iron accounted for 13%, 43% and 48% of the total load, respectively. In the lower reaches, downgradient of the mining areas, diffuse loads were 10%, 30% and 44% of the total load for zinc copper and iron respectively. Based on these results, diffuse contamination would have to be addressed in order to meet environmental quality standards (EQS) in the Avoca River.

METHODOLOGY

The study area, approximately 1.5 km in length, extended from 320 m upstream of White Bridge to an abandoned coal yard, downgradient of the mining areas (Transect 1 to Transect 5, see Figure 1). Previous studies have found that contamination impacts from the mining areas on the Avoca River begin to occur downstream of T1. Data collected at T1 formed the baseline to which the downstream transect locations were compared. Measured slugs of Fluorescein (FL) and Rhodamine WT (RWT) dye were mixed into the Avoca River downstream of the Avonmore and Avonbeg River Confluence (see location on Figure 1); 800 m upstream of the first transect location (T1). Three GGUN-FL30 fluorometers, provided by the Geological Survey Ireland, were employed to record the concentration of dye(s) at 10 second intervals within the river (Figure 2). A total of eleven in-channel tracer tests were completed over a four day period during river flow conditions ranging from 4 m^3/s to 6 m^3/s. Gaining and or losing river stretches were identified using the recorded or calculated flow rate at each river transect. The recorded flows at the EPA hydrometric station 'White Bridge GS (10044)' were available at 15-minute intervals and projected to T1. The flow rate (m^3/s) at each downstream transect was established by integrating the dye breakthrough curves, as follows:

$$Qd = \frac{Au(Qu)}{Ad}$$

Where, Q_d = Flow rate at the downstream transect
A_u = Area under the curve at the upstream transect
Q_u = Flow rate at the upstream transect
A_d = Area under the curve at the downstream transect

Figure 2 Fluorescein (FL) dye in the Avoca River upstream of White Bridge. Inset photo: GGUN-FL30 fluorometer probe (courtesy of the Geological Survey Ireland).

Representative composite water samples were collected across the river at each transect location and point source discharge. Analyses (dissolved concentrations after field filtering) were performed for the following parameters: Al, Sb, As, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, V and Zn. Flow rates multiplied by dissolved metal concentrations determined the mass load of dissolved metals (kg/day) in the Avoca River.

RESULTS

The findings presented in the following sections are for dissolved zinc only. Additional parameters, notably dissolved copper and iron are discussed in relation to T2 to T3.

RIVER FLOW ASSESSMENT

No significant gains or losses in river flow were recorded between T1 and T2 with the percentage difference in flow ranging from -0.04% to 8% and is considered to be within the margin of error (i.e. the accuracy of the measurements). A notable increase in flow magnitude was recorded between T2 and T3 with a maximum increase in flow of 22%. The river segment, T2 to T3, captured flow and contamination through the Deep Adit Spoils Area and Mill Race in East Avoca and the Emergency Tailings Area in West Avoca (all shown on Figure 1). The hydraulic communication between the river and groundwater is of primary importance in evaluating potential contaminant loads to the river from diffuse groundwater flow. Concurrent hourly groundwater level recordings in the Deep Adit Spoils Area and river water levels at White Bridge GS (10044), indicate that a positive gradient existed for over 75% of the 2013-2015 period at monitoring well DA2 (24.9 m bgl) and over 95% at monitoring well DA1 (12 m bgl). At the Emergency Tailings Area in West Avoca, a positive gradient existed for over 99% of the monitoring period.

Further downstream, between T3 and T4, a 10% decrease in flow was calculated. Three tests undertaken between T3 and T5 indicate an average increase in flow of 5.3% which is within the margin of error. Therefore, based on the calculated flows between T3 and T4 (losing stretch) and T3 and T5 (no significant change), the T4 to T5 river stretch is likely gaining in magnitude.

MASS BALANCE ANALYSIS

Increases in dissolved zinc load were calculated at each monitoring location adjacent to and downgradient of the mining areas, as shown in Figure 3. T1 was located approximately 310 m upstream of T2. No point discharges exist within this river stretch so diffuse groundwater flow was the only potential mass input to the river. However, between T1 and T2, increases in the mass load of dissolved zinc were negligible. Therefore, contamination from the mining areas is most prevalent downstream of White Bridge (T2).

To quantitatively assess the impact of the Deep Adit Spoils Area and Mill Race on the Avoca River, T3 was installed approximately 340 m downstream from T2. The primary source of AMD from East Avoca drains through the Deep Adit and discharges to the river 168 m downstream of T2. A net gain in dissolved zinc load, ranging from 339% to 475%, was evident in each of the four tracer tests undertaken between T2 and T3.

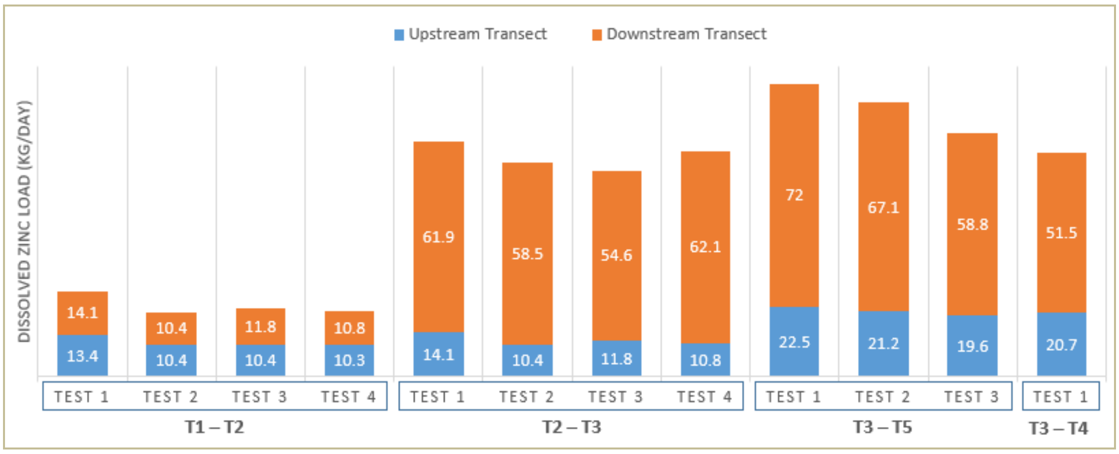

Figure 3 Total mass loading of dissolved zinc

T5 was installed 755 m downstream of T3 and 415 m downstream of the Road Adit discharge to the Avoca River (Road Adit Confluence in Figure 1). The Road Adit discharge is the primary point source of AMD from West Avoca. An increase in dissolved zinc load was calculated for each of three tracer tests, ranging from 200% to 221% with an average increase of 213%. Potential diffuse sources of dissolved zinc load include the Emergency Tailings Area, groundwater seeps in the vicinity of the Ballygahan Adit and spoil material located at several areas in West Avoca. One tracer test was completed between T3 and T4, located 70 m downstream of the Road Adit discharge. Loading results indicate a net gain, even though the river was losing flow in this stretch. Dissolved zinc load increased from 20.7 to 51.5 kg/day which is a 149% increase. The apparent contradiction of mass being gained and flow being lost may be due to groundwater seepage in the Emergency Tailings Area and at Ballygahan Adit which may be adding metal load to the river, while loss to groundwater may be occurring in separate sections of the river stretch.

DIFFUSE CONTAMINATION

To quantify the extent of diffuse contamination within each designated river stretch, the calculated mass load of dissolved zinc at each point (adit) discharge was removed from the analysis. Results are shown in Figure 4.

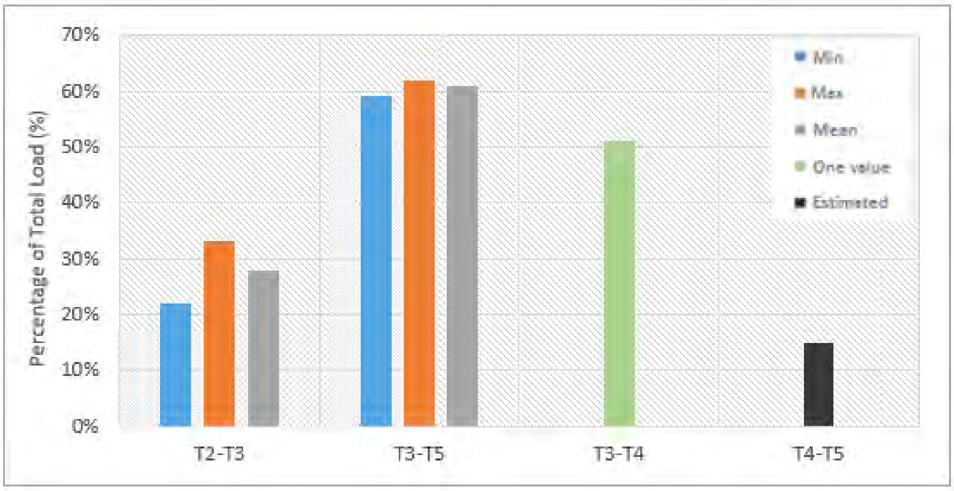

Figure 4 Diffuse dissolved zinc load as a percentage of total dissolved zinc load

No diffuse loading analysis was conducted at T2 due to the negligible increases in dissolved metals in the upstream segment. Of the total zinc load occurring between T2 and T3, an average of 28% was due to diffuse contamination i.e. the Deep Adit discharge accounted for 72%. At T5, the calculated mass load of dissolved zinc at the Road Adit was removed from the analysis. Between 59% and 62% of the total load occurring between T3 and T5 was due to diffuse flow. Because a distance of 755 m existed between T3 and T5, further tests and evaluations were conducted to identify where within this river stretch the most extensive contamination was occurring. One tracer test conducted between T3 and T4 found diffuse contamination accounting for 51%. Furthermore, based on the tests undertaken between T3 and T4 and between T3 and T5, approximately 15% of the total dissolved zinc load at T5 was occurring downstream of T4.

Estimated Avoca River Water Quality

Predicting the concentration of dissolved metals which occur through diffuse contamination alone provides an estimation of potential future conditions whereby, point sources currently discharging to the Avoca River are captured and treated. Estimated concentrations of dissolved zinc due to only diffuse contamination are shown in Figure 5.

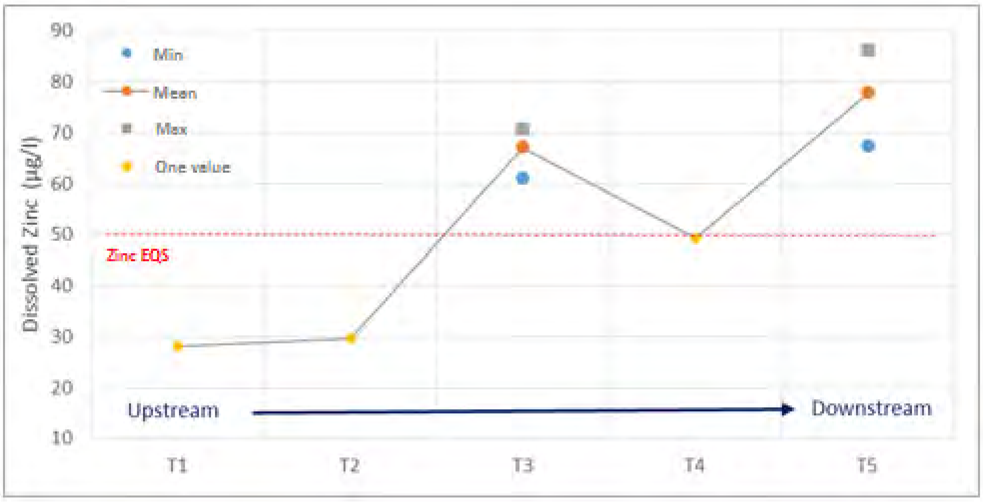

Figure 5 Estimated concentration of dissolved zinc from diffuse contamination

Between T1 and T2 no point sources exist. Dissolved zinc concentrations at T1 (28.2 µg/l) represent background levels in the Avoca River. Concentrations at T2 (29.7 µg/l) account for background levels and diffuse contamination occurring downstream of T1 (minimal). Concentrations at T1 and T2 are significantly below the EQS for ecological protection of 50 µg/l[1]. Assuming no point discharges (i.e. Deep Adit), the estimated minimum concentration of dissolved zinc at T3 was 61.1 µg/l. The estimated maximum (70.6 µg/l) and mean (67.1 µg/l) concentrations were 29% and 25% greater than the environmental standards, respectively. Both the Deep Adit and Road Adit discharges were removed from the analysis undertaken at T4 and T5. At T4, the estimated concentration of dissolved zinc decreased to 49.3 µg/l. Further downstream at T5, the minimum concentration of dissolved zinc was 67.3 µg/l. The estimated maximum (86.2 µg/l) and mean (77.8 µg/l) concentrations of dissolved zinc were 42% and 36% higher than the environment standards respectively.

TRANSECT 2 – TRANSECT 3

Determining the impact of the major spoil piles at the Deep Adit and East Avoca as well as the recently (2014) contaminated Mill Race area was of primary importance. Four tests were undertaken between T2 and T3 (Figure 1). The loading results for dissolved copper, iron and zinc indicate a net gain between transect locations in each test. The increase in dissolved copper load ranged from 59% to 109% with an average increase of 85%. The dissolved iron load increased by 63% to 114% with an average increase of 90%. The most significant increase was for zinc with increases ranging from 339% to 475% and an average increase of 409%.

The Deep Adit discharge, located approximately 165 m downstream of T2 was the only point source discharging to the river between T2 and T3 in September 2016. Dissolved metals identified as occurring by diffuse source contamination in each of the four tests are presented in Figure 6. Recorded concentrations of dissolved cadmium, cobalt, manganese, nickel and arsenic were below the environmental standards at T3 and are included for reference purposes only. Figure 6 shows that up to 49%, 53% and 33% of dissolved copper, iron and zinc were due to diffuse inflow, respectively. Using the average over the four tests, 28% of dissolved zinc load at T3 is due to diffuse sources. The proportion of dissolved copper and iron load is higher at 41% and 46%, respectively.

[1] Based on the measured hardness in the Avoca River.

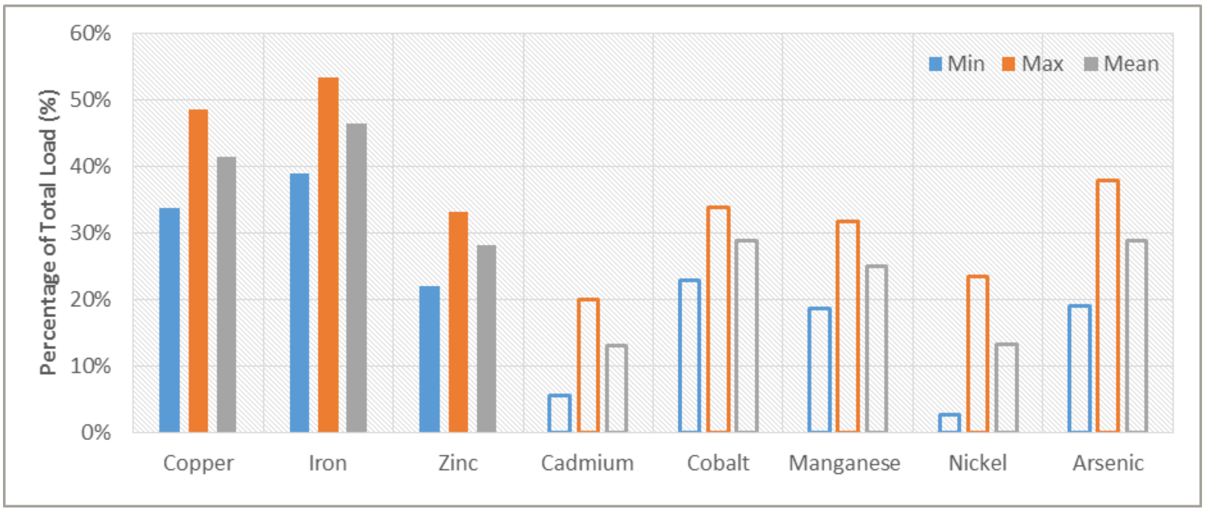

Figure 6 Diffuse load as a percentage of the total load increase between T2 and T3

Based on the extent of diffuse contamination between T2 and T3, dissolved copper, iron and zinc were identified as exceeding the EQS in the Avoca River, in the hypothetical situation where the Deep Adit was not discharging into the river. The minimum concentration of dissolved copper (5.07 µg/l) marginally exceeded the EQS of 5 µg/l[2]. For dissolved zinc, a minimum concentration of 61.1 µg/l was estimated which exceeds the EQS of 50 µg/l. The maximum (70.6 µg/l) and mean (67.1 µg/l) concentrations of dissolved zinc were 29% and 25% higher than the environment standards respectively.

COMPARISON OF THE 2007 AND 2016 TRACER STUDIES

Although not directly comparable due to differences in methodology and design, the findings from the 2007 and 2016 tracer studies are in general agreement. In both studies, a progressive increase in the mass load of dissolved metals was calculated at each monitoring location adjacent to and downstream of the mining areas. Furthermore, both studies identified diffuse groundwater flow as a significant source of contamination to the Avoca River. As shown in Table 1, the percentage of dissolved zinc load of total load is significantly higher in 2016, particularly in the lower reaches of the river where an increase was observed from 10% in 2007 to 61% in 2016. Variances can be attributed to a number of factors including changing environmental conditions, flow conditions and sampling methodologies. Significantly, both studies estimated that concentrations of dissolved copper and zinc would exceed the EQS of 5 µg/l and 50 µg/l respectively, even if point sources currently discharging to the river were captured and treated.

Table 1 Comparison of Diffuse Loads between the 2007 and 2016 Tracer Studies

Dissolved Metal	Comparison of T1-T2 (2007) and T2-T3 (2016)		Comparison of T2-T5 (2007) and T3-T5 (2016)	
	2007	2016	2007	2016
Copper	43%	41%	30%	51%
Iron	48%	46%	44%	61%
Zinc	13%	28%	10%	61%

[2] Based on the measured hardness in the Avoca River.

CONCLUSIONS

Both tracer studies (2007 and 2016) have established that diffuse contamination accounts for a significant proportion of the total dissolved metal load in the Avoca River. In the upper section of the study stretch (T2 to T3), diffuse zinc load was on average, 28% of the total increase in load in September 2016. In the lower section (T3 to T5), this value increased to 61%. Predicted concentrations of dissolved zinc in the Avoca River, excluding the concentrations measured in the Deep Adit and Road Adit discharges, exceed the EQS at a number of transect locations downstream of T2 (located directly upstream of White Bridge). The implication is that both point sources and diffuse sources of dissolved metals need to be addressed for the water quality of the Avoca River to be returned to an acceptable level.

ACKNOWLEDGEMENTS

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IMPLEMENTING GUIDANCE ON THE AUTHORISATION OF DISCHARGES TO GROUNDWATER – EXPERIENCE FROM ONE LOCAL AUTHORITY

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ABSTRACT

Two new guidance documents to assist in the technical assessments required in authorising discharges to groundwater were published in 2011. "Guidance on the Authorisation of Discharges to Groundwater" was issued by EPA and "Guidance, Procedures and Training on the Licensing of Discharges to Surface Waters, Groundwater and to Sewer for Local Authorities" (Vol.1 and Vol.2) was issued by the Local Authority Services National Training Group (LASNTG). This article outlines experience in implementing this guidance in Co. Meath and provides a case study on assessing an application for licence to discharge to groundwater for a proposed discharge of 18m^3/day.

INTRODUCTION

Two new guidance documents to assist in the technical assessments required in authorising discharges to groundwater were published in 2011. "Guidance on the Authorisation of Discharges to Groundwater" was issued by EPA and "Guidance, Procedures and Training on the Licensing of Discharges to Surface Waters, Groundwater and to Sewer for Local Authorities" (Vol.1 and Vol.2) was issued by the Local Authority Services National Training Group (LASNTG). While the EPA guidance is aimed primarily at EPA staff it is also intended to assist local authorities and other environmental professionals. The LASNTG guidance, as regards discharges to groundwater, draws on and aligns closely with the EPA guidance. These guidance documents were used as the basis for training courses delivered by LASNTG in 2011 to Local Authority staff involved in discharge licensing under the Local Government (Water Pollution) Act 1977, as amended.

The guidance documents are designed to bring a consistent approach in how discharge to groundwater applications are prepared, assessed and determined, and to ensure that assessments and decisions are consistent with the requirements of the European Communities Environmental Objectives (Groundwater) Regulations, 2010 (S.I. No. 9 of 2010), the EU Groundwater Directive (2006/11/EC) and ultimately the EU Water Framework Directive (2000/60/EC). The guidance gives the geotechnical view to compliment earlier publications such as EPA Wastewater Treatment Manuals – Treatment Systems for Small Communities, Business, Leisure Centres and Hotels (EPA, 1999).

THE GUIDANCE

Central to this framework is the "prevent or limit" objective defined in Article 6 of the EU Groundwater Directive - to prevent inputs of hazardous substances to groundwater and to limit inputs of non-hazardous substances so inputs do not cause deterioration in groundwater status or significant and sustained upwards trends in pollutant concentration in groundwater. Central also is the Source – Pathway – Receptor (SPR) model which informs the assessment of the risk potentially posed by the discharge, taking account of the nature of the discharge, the hydrogeological context and various receptors - groundwater bodies, abstractions, surface water bodies, groundwater dependent terrestrial ecosystems.

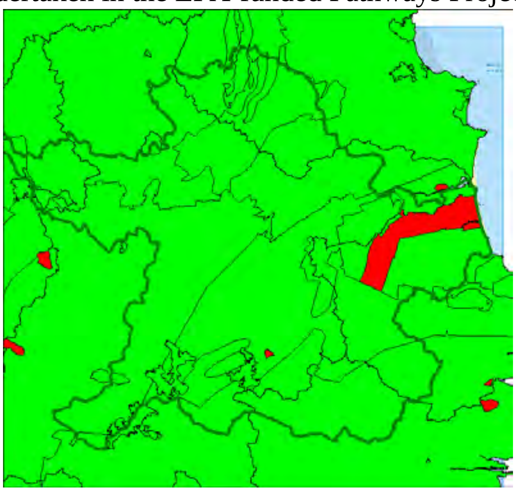
The guidance sets out that the risk to groundwater from a proposed discharge is screened, based on a combination of SPR risk factors and that the outcome of this screening will then determine the level of technical assessment, and the level of site-specific investigation required in each case. Developing a Conceptual Site Model is an important stage as this forces a consideration of the linkages and pathways at the site and will highlight uncertainties. Tier 1, 2 and 3 levels of assessment, equivalent to Low, Moderate and High Risk scenarios, are detailed with examples of site investigation requirements and considerations under each Tier. The assessments are designed to demonstrate the suitability of the site to adequately infiltrate the effluent hydraulically and to attenuate the effluent to a standard protective of receptors and environmental objectives, with a higher burden of proof for higher risk discharges. At the lower degree of risk a Tier 1 assessment follows the 2009 EPA Code of Practice for assessment, while the higher tiers add additional requirements on the extent of site characterisation and impact prediction.

The risk screening process with the SPR risk factors to be considered is set out in Figure 7 of the EPA guidance and is also reproduced in the LASNTG guidance. Risk factors to be considered include pollutant type and concentrations, discharge rate, presence or absence of hazardous substances, minimum separation distances, groundwater vulnerability, aquifer type, proximity to potentially sensitive receptors, discharge concentrations relative to receptor-based standards, groundwater capacity.

The guidance gives recommended tiers of assessment across a range of example risk scenarios, including thresholds based on discharge volumes, however it recognises also the "assignment of risk is subject to some degree of professional judgement". There is obviously a balance to be struck between the advantages of a highly prescriptive "banded" approach to what is required and a somewhat more flexible approach to account for the variations that can occur in the combination of site settings, discharge scenarios and uncertainties.

COUNTY MEATH AND CURRENT WFD CONTEXT

In Water Framework Directive terms, the majority of groundwater bodies in Co. Meath are currently classed as Good Status, in line with the situation nationally. This contrasts with the status of river waterbodies where a majority in Meath are classed at less than Good Status. The rivers in the east and south-east of the county tend to have higher phosphate concentrations and there is correlation between this and the occurrence of poorly drained soils (and low groundwater vulnerability) in these areas. Such linkages are expressed in detail in Critical Source Area and Pollution Impact Potential mapping undertaken in the EPA-funded Pathways Project.



Base map © Ordnance Survey Ireland & Government of Ireland,2017/31/CCMA Meath County Council

Figure 1. Groundwater Body Chemical Status 2010-2015, source EPA.

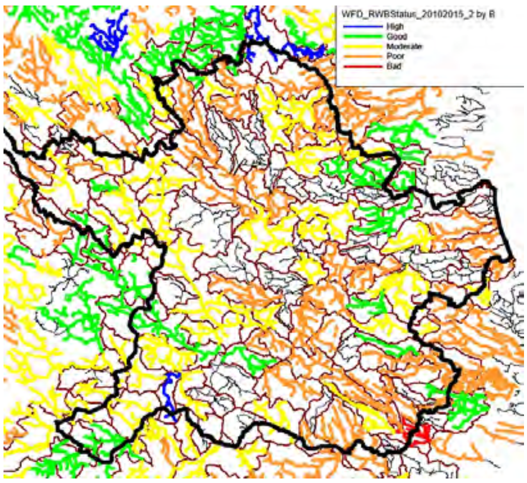


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Figure 2. River Waterbody Status 2010-2015, source EPA

SOME POINTS FROM EXPERIENCE TO DATE ON GROUNDWATER DISCHARGE ASSESSMENTS

The LASNTG guidance on licensing discharge to groundwater issued in 2011 was accompanied by revised application forms and applicant guidance (in Volume 2), in respect of applications for licence to discharge effluent to waters under Section 4 of the Local Government (Water Pollution) Act 1977, as amended. The application forms are more detailed than application forms commonly in use prior to 2011. This feature, combined with the detailed application guidance that is available for prospective applicants to view on-line at pre-application stage, has helped application assessments as there is a better level of information provided in the initial applications.

To date, most of the larger discharge to groundwater applications dealt with in Meath have been at Tier 2 level of assessment. Once the applications go beyond a standard Tier 1 assessment, there is an increased importance on the applicant's consultant having the necessary hydrogeological expertise to prepare the applications, from the risk-screening to obtaining appropriate site-specific data for valid assessment of potential impacts.

Even with larger-scale discharges, the assessment is still about demonstrating "site suitability". However a site with T-test values in the range 50-75 min/25mm, which would be deemed suitable for discharge to ground via polishing filter after a secondary treatment system in the case of a single house, requires more detailed testing, to establish whether it could accept and treat a larger scale discharge. In one such case further testing to measure Field Saturated Hydraulic Conductivity (K_{fs}) by falling head tests in shallow boreholes in the subsoil found poorer K_{fs} values than was indicated by the standard T-tests, and the site was deemed unsuitable to accept a large scale discharge.

Conversely, a proposed discharge of $18m^3$/day in a setting with >5m depth of freely draining soil and subsoil (e.g T-tests 10 - 20 min/25mm), over a moderately productive aquifer poses a lower risk than the "borderline percolation" site, with implications for the nature of additional site investigations.

Elevated nitrate or ortho-phosphate is not a prevalent issue across most groundwater bodies in Meath and mass balance calculations on the predicted impact of the discharge at waterbody scale generally show acceptable impacts, once the site conditions have passed suitability for percolation and attenuation. The local-scale issues can be more important, such as ensuring adequate treatment and adherence to minimum separation distances in Groundwater Protection Responses to protect a down-gradient drinking water supply.

The contrast in the degree of compliance with WFD objectives between surface waters and groundwaters might suggest there is effectively much more assimilative capacity and headroom to environmental quality standards in the groundwater realm compared to surface waters, and this is true to an extent. The "combined approach" to setting discharge emission limit values (ELVs) for discharge to surface waters, arising from Art.10 of the EU Water Framework Directive, (ELVs set by the stricter of criteria such as BAT or limits consistent with receiving water achieving Environmental Quality Standards), means that in the case of a proposed discharge to a minor stream with already elevated background concentrations, the discharge may only be licensed with extremely tight emission limits, potentially at the margin of technical feasibility. In these cases prospective applicants would be advised to investigate the feasibility of a discharge to groundwater as a potentially more workable solution. In some cases this has proved to be a satisfactory route. Difficulties can arise where local streams are minor and impacted by high background nutrient concentrations, typical in some poorly drained soils areas, but where the poorly drained soils and subsoils result in inadequate infiltration capacity where a discharge to groundwater could not be permitted.

Groundwater vulnerability rating needs to be reviewed after site investigations if depth to bedrock is found to be shallower than previously indicated at desk-survey stage, this can be relevant at High/ Extreme groundwater vulnerability settings. The transition zone in Namurian shale bedrock at certain sites can be highly weathered and fractured, with a less obvious delineation from overlying subsoil. Excavations for trial holes can readily cut through this material.

There may be scope for further guidance in the case of small-scale discharges such as vehicle wash bays in unsewered areas discharging to percolation areas - worked examples in relation to the "prevent" requirement, or definitions of best practice. For example, Planning guidelines issued in 2016 by the Dept. of Agriculture, Environment and Rural Affairs in Northern Ireland sets out a hierarchy of preferred disposal options for this type of effluent. This guidance sets as the fourth (least preferable) option for disposal of wash water effluent: "Consent under the Water (NI) Order 1999. This will only be considered either where detergents will not be used or where the effluent is going to a treatment system that has a separate nutrient supply (e.g. sewage) and has the ability to reduce the combined biological oxygen demand (BOD) to within consent limits."

Cases where pre-existing discharges require upgraded treatment, but the area available for percolation is constrained, present difficulties. In some cases water usage metering and active measures to reduce water consumption and thus effluent volumes help to lower effluent loading rates.

Irish Aquifer Properties – A reference manual and guide (EPA/GSI, 2015) provides a useful background and reference figures for parameters such as aquifer permeability which can help in assessing a site and submitted details.

The assessments can take on differing priorities depending on the key receptors identified– e.g a discharge to groundwater in a coastal location near a beach, with groundwater flow towards the coast, would require an emphasis on demonstrating adequate effluent attenuation for microbial quality, protective of bathing waters and beach users, rather than additional measures for phosphorus removal.

CASE STUDY

A pre-existing discharge licence permitted discharge of 20m^3/day of treated domestic effluent to surface waters. The receiving waters were a minor unmonitored tributary of the R. Skane (in the Boyne catchment) with only limited dilution/ assimilative capacity. Upgrade of the existing WWTP (septic tank plus peat bed filter discharging to stream) was required to achieve improved discharge standards. Following initiation of licence review, site investigations began in 2011 to investigate the feasibility of a discharge to groundwater.

Site investigations according to EPA 2009 Code of Practice found favourable site conditions for discharge to groundwater. Trial holes (to 2.3-2.7m bgl) were excavated and percolation testing carried out at 4 locations on the site. Average T-test values at the 4 locations were determined as 6.7, 18, 9 and 13.7 min/25mm. Site investigation recorded no visual indications of poor drainage such as vegetation indicators or drainage ditches.

GSI mapping gives bedrock as Namurian Undifferentiated, Aquifer is classed as Poorly Productive (Pl) generally unproductive except for local zones. The underlying groundwater body is Hill of Tara, EA_G_028, (area 21 km2, WFD Good Status). GSI summary of initial characterisation for this groundwater body outlines regional groundwater flow direction to the north and west towards R. Boyne, but notes that local groundwater flow will be dictated by local topographic, and hence hydraulic gradients, which will converge at rivers. This also notes that a high proportion of the recharge to the aquifer will discharge rapidly to surface watercourses via the upper layers of the aquifer.

The proposed location of the soil polishing filter is mapped as High groundwater vulnerability and underlain by subsoil type GLs (gravels derived from limestones, glaciofluvial sands and gravels) and soil group Renzinas, Lithosols (BminSW), but close to a boundary to Moderate groundwater vulnerability, TLs subsoils (till derived from limestone) and soils of Grey Brown Podzolics, Brown Earths (BminDW), from GSI/Teagasc mapping. Both soil types are well drained.

Groundwater Protection Response from Groundwater Protection Schemes (DELG/EPA/GSI) for this scenario of Pl/H is R1 – acceptable subject to normal good practice (ie system selection, construction, operation and maintenance in accordance with EPA 2009).

Subsoil sample testing from trial holes across 4 locations according to the GSI flow chart based on BS5930:1999 found subsoils of SILT and sandy SILT/CLAY to approx 1.8m bgl, with gravelly SILT/CLAY or gravelly CLAY intermixed with cobbles below 1.8m. No mottling or groundwater was encountered in trial holes (to 2.3m – 2.7m bgl). One borehole was drilled to south of SPF location, encountering bedrock at 10m bgl and recording subsoils of good to average percolation from 0-6m (SILT/CLAY intermixed with gravels), and poorer percolating material and clays below 6m.

Groundwater flow direction at local scale is inferred as towards the north-east, based on topography and the surface stream approx 100m east of the site.

The site is served by mains water supply. One well was identified approx 250 m to the north (side or downgradient) and one well approx 500m to south (upgradient), and a disused well on-site at 30m to south, (side or upgradient). Groundwater sampling from the disused well found hard water with low nutrient concentrations (PO_4-P < 0.016mg/l, NO_3-N < 0.1 mg/l). Potential receptors include the underlying aquifer, downgradient well 250m to north and local surface stream approx 100m to east of the proposed discharge. Distances to the downgradient well (250m) and the disused well on site (30m) exceed the minimum separation distances specified in Groundwater Protection Responses for T Values < 10 , i.e. 60m for downgradient well, reducing to 30m where there is >8m of soil and subsoil above bedrock and water table >2.0m (as present here), and 25m for side-gradient well.

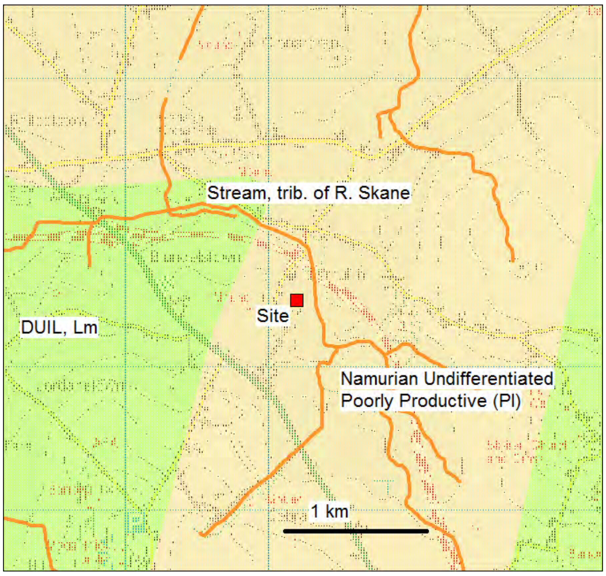

Fig. 3. Site location, GSI bedrock aquifer map, surface streams. Source GSI, EPA, OSI.

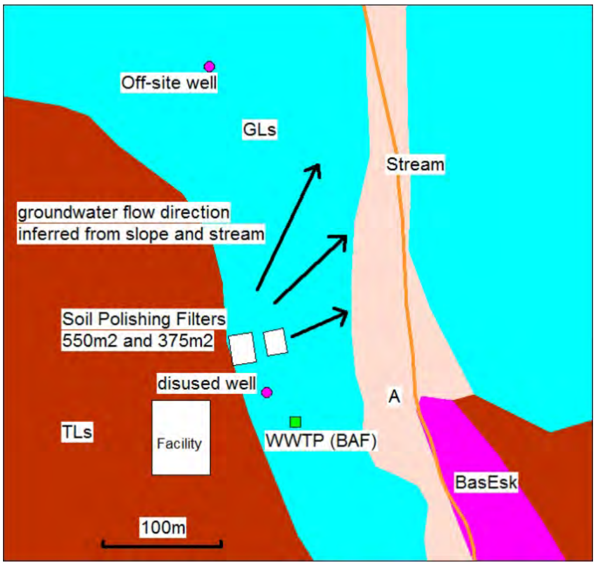

Fig. 4. Site layout and groundwater flow direction over GSI/Teagasc subsoil mapping. Source GSI, Teagasc, EPA.

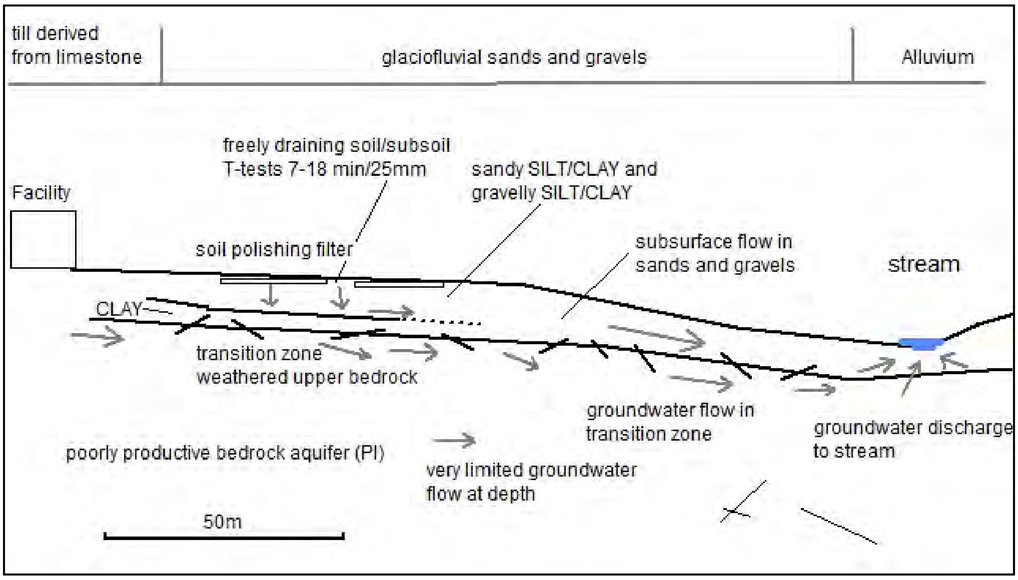

Fig. 5. Conceptual Site Model showing soil polishing filters (source), subsoils, transition zone and bedrock (pathways) and adjacent stream and aquifer (receptors). Note lateral extent or continuity in clays at >6m bgl is uncertain but stream remains as most prominent receptor.

The proposed wastewater treatment system comprises of a 100 PE Biofilm Aerated Filtration system (BAF), with 2 primary sedimentation chambers of 18m^3 each, followed by secondary biological treatment with submerged aeration to suspended biomedia, followed by clarifier and pumping to soil polishing filters of combined area of 925m^2. This gives a loading rate to the soil polishing filter of 20L/m^2/day, which accords with the minimum polishing filter areas for T values of 3-20 in Table 10.1 of Code of Practice, and with Long Term Acceptance Rates in Table E2 of Guidance on Authorisation of Discharges to Groundwater. The soil polishing filter (tertiary treatment) is designed as a pressurised system, 32mm pipework with 6mm orifices, laterals at 0.6m spacing, over 250mm gravel (10.1.1(b) of EPA Code of Practice), total area of 925m^2 across 2 separate polishing filters, with effluent distribution to polishing filter zones by splitter and timed dosing. Site investigations show the depth of free-draining soils above water table and bedrock is well in excess of 0.9m minimum required in the Code of Practice and R1 Groundwater Protection Response.

Photo 1: Dec 2013, preparing the soil polishing filter area.

Photo 2: Feb 2014, installing the pressurised distribution pipework in one of the soil polishing filters.

Integrating the desk study and site investigation results indicates that treated effluent percolating beneath the soil polishing filter will move vertically through subsoil with good percolation rates over the first 6m of depth. Below 6m reduced percolation is expected based on borehole findings. The ground slopes north-eastwards towards the minor stream, and local subsurface and groundwater flow could be expected to move towards this stream, particularly in the high permeability glaciofluvial sands and gravels. This would facilitate lateral movement dictated by any underlying lower permeability layers and reduces the likelihood of excessive mounding under the SPF which could be a risk given the lower permeability at depth and the poorly productive aquifer. The stream then becomes the most prominent receptor. There is uncertainty over the lateral extent or continuity of the poorer percolation layer found below 6m. This could influence the proportion of the flow path in the overlying glaciofluvial subsoils vs the proportion in the transition layer of weathered upper bedrock, however both pathways lead towards the stream.

Estimates of the flux of discharge components into groundwater and into the nearby stream were made using proposed emission limits and assumed attenuation rates for NH_4, PO_4 and NO_3 at 90%, 90% and 0% respectively. Mass balance dilution estimates at groundwater waterbody scale (21km^2 area) are presented below, using a recharge rate of 100mm/year to the poorly productive aquifer. This indicates the input uses 18%, 14% and 0.5% for NH_4, PO_4 and NO_3 respectively of theoretical headroom to groundwater threshold values. However this would represent an over-estimate of the flux from the discharge into the aquifer – the limited recharge rate reflects the low aquifer permeability (with resulting “rejected recharge”) and in reality a significant portion of the discharge will be transmitted in subsurface and transition zone pathways to surface waters. The attenuation rates are likely higher also, given soil and subsoil conditions, with potential groundwater impact further lowered.

Ground Water Body			EA_G_028						
GWB Area			21	km2					
Avg Recharge (m/yr)			0.1	m/year					
GWB recharge			5753	m3/day					
Effluent Discharge Rate			18	m3/day					
Discharge Volumetric Dilutio			0.31						
Resulting GWB concentrations									
							0.3% dil		
Parameter	Unit	ELV	Load Reduction - via SPF and subsoil	Conc in discharge to GWB	Estimated backgroun d conc (0.75* TV)	Groundwat er Threshold Values	Estimated Resulting Groundwat er Conc over whole GWB	Actual increase in conc (mg/L)	Headroom (mg/L)	% Headroom used
NH4-N	mg/L	10	90	**1**	0.049	0.065	0.052	0.003	0.016	17.8
MRP-P	mg/L	4.4	90	**0.44**	0.026	0.035	0.027	0.001	0.009	13.8
NO_3-N	mg/L	10	0	**10**	6.39	8.52	6.40	0.011	2.13	0.5
Groundwater background conc estimated as 0.75 x Groundwater Threshold Values in European Communities Environmental										

Fig. 6. Mass balance calculation to estimate discharge impact on underlying aquifer.

Emission limits specified in the discharge licence were BOD 10mg/l, COD 50mg/l, SS 12mg/L, pH 6-9 NH_4-N 10 mg/l, NO_3-N 10 mg/l, Total P 4.4 mg/l, OFG 10 mg/l.

As the conceptual site model indicates the stream as a prominent receptor, a mass balance calculation of the impact on in-stream concentrations is instructive. 95%ile stream flow in this un-gauged subcatchment was estimated from EPA on-line HydroTool application at 1382m^3/day (12km^2 catchment). Using a worst-case scenario where 18m^3 treated effluent from the soil polishing filter ultimately inputs as a combination of subsurface and groundwater flow to the stream, gives a dilution ratio of 1.3% treated discharge and 98.7% stream flow at maximum discharge and 95%ile stream flow. Resulting mass balance calculations in line with LASNTG surface water discharge guidance, indicate that the input could potentially use 46% and 33% of NH_4 and PO_4 headroom. This assumes

90% attenuation in the SPF (citing Table D5 in the groundwater discharge guidance, based on Gill, et al 2009). However given the significant depth of suitable unsaturated subsoil below the polishing filter a higher attenuation rate is likely justified, and a 95% rate (over the course of the full pathway vertically and laterally from SPF to stream) brings estimated impacts below 20% headroom consumption (NH_4 at 20% headroom consumption and PO_4 at 14% headroom consumption). The necessity for a compliance monitoring borehole between the SPF and the stream could be argued but in this case monitoring of the standard of discharge after secondary WWTP (prior to SPF) is considered to provide appropriate control.

The emission limits set in this licence were driven primarily by EQSs for the surface water receptor. At one level the discharge could still be regarded as a discharge to surface waters, but with the intervening soils and subsoils as the final treatment step before the stream. Without this stage emission limits for a direct discharge to the stream would have been approximately 20 times lower and technically more challenging.

The level of site-specific data used in this case does not address all potential items at Tier 2 (e.g no bedrock permeability testing), however there are a balance of factors in assessing the risk – the scale of discharge volume and proximity to stream as moderate risk factors vs standard of treatment (tertiary), significant underlying suitable subsoils, distances to drinking water receptors indicating lower risk. The conceptual site model has facilitated identification of keys receptors and risks, and simple mass balance calculations have been used to check that predicted impacts are acceptable.

CONCLUSIONS

The guidance documents issued in 2011 have facilitated an improved level of assessment of discharge licence applications for discharges to groundwater. This guidance has also been used in reviews of pre-existing licences for discharge to waters and in some cases this has facilitated discharges into surface waters of limited assimilative capacity being re-configured as discharges to groundwater, thus reducing pressures on the surface waters. Developing the Conceptual Site Model so that pathways to the key receptors are identified is a critical stage which underpins the assessment.

There may be scope for further guidance on issues such as risk screening in determining the appropriate level of detail for site investigations and assessment (Tiers of Assessment) and on best practice for cases such as small scale discharges of non-domestic effluent from wash bays.

ACKNOWLEDGEMENTS

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SESSION IV

SOCIO-HYDROGEOLOGY: BRIDGING THE GAP BETWEEN SCIENCE AND SOCIETY TO BETTER ADDRESS AQUIFER CONTAMINATION

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ABSTRACT

Socio-hydrogeology is proposed as a way to go beyond the state of the art of classical hydrogeological investigations that will contribute effectively bridging the gap between science and society. To this end, socio-hydrogeology foresees the integration of specific social analysis (i.e. Stakeholder Network Analysis and public engagement) to hydrogeochemical and hydrogeological assessments aimed at defining the baseline characteristics of a studied system and the deviations from natural conditions due to human activities. This approach was preliminary tested in the Grombalia aquifer (Tunisia), chosen as a pilot case study representative of the issues shared by most of the coastal aquifers in the Mediterranean basin (i.e., aquifer pollution and salinization, water overexploitation, saline-water intrusion, and agricultural return flow). Results show that both Stakeholder Network Analysis and public participation of local actors were fundamental for the effective development of the hydrogeological investigation. In particular they permitted to: (i) obtain relevant information to support data interpretation, and eventually guaranteed the correct assessment of contaminant sources in the studied area; (ii) create a momentum of dialogue between the research team and water end-users, thus paving the way for adequate knowledge transfer and capacity building on environmental protection; and (iii) attain explanations for otherwise unexplained social and political dynamics governing the local groundwater sector.

INTRODUCTION

Integrated water resources management, groundwater governance, sustainability, aquifer contamination, seawater intrusion, climate change. These are some of the currently trending topics in hydrogeology, as reflected by their extensive use as keywords in most of the recently published literature. Indeed, hydrogeologists are at the forefront of guaranteeing the long-term sustainability of aquifers worldwide. But questions arise when the outcomes of their investigations have to be concretely translated into effective science-based management practices, or when they have to ensure that their work really reaches water end-users and all those eventually affected by new water quality and quantity control measures.

Indeed, the most effective way is to commit themselves to bridging gaps between science and society. This is the aim of “socio-hydrogeology”, a new approach to groundwater investigations promoting the incorporation of the social dimension into hydrogeological studies willing to provide management practices with better support (Re, 2015).

Socio-hydrogeology proposes to complement hydrogeological investigations with a more comprehensive assessment of the socio-economic implications of the (ground)water problems in question. In agreement with the general definition of socio-hydrology —the science of people and water (Sivapalan et al. 2011)— socio-hydrogeology aims at studying the mutual relations between people and groundwater by effectively including the social dimension in hydrogeological investigations. Overall, this process may ensure that the results of scientific investigations are not only based on real needs and local knowledge, but are also adequately disseminated to groundwater end-users.

Indeed, hydrogeologists can advocate for groundwater management and protection by promoting bottom-up approaches that embed local know-how into management strategies. As many hydrogeologists spend substantial time in the field, they are often the first point of contact for well holders, farmers and other water end-users. Therefore, by allocating specific time to structured interaction with the concerned stakeholders prior to and during hydrogeological investigations, they can maximize the use of their hydrogeological information and research outcomes. In other words, they can act as mediators between theory and practice, or between the problem and the (potential) proposed solution to issues under investigation.

This paper aims at presenting the main features of socio-hydrogeology together with the main outcome of its first case study application in the Grombalia Basin (Tunisia).

SOCIO-HYDROGEOLOGY: WHY WE SHOULD ALL ENGAGE FOR GROUNDWATER PROTECTION?

As previously mentioned, socio-hydrogeology was proposed as a new way to contribute bridging the gap between science and society, by coupling classical hydrogeological approaches with social-sciences tools, and it is centered on the role of hydrogeologists as advocates for public engagement and groundwater protection (Re, 2015). In particular, socio-hydrogeology proposes that any hydrogeochemical and hydrogeological assessment, aimed at defining the baseline characteristics of the studied groundwater system and at evaluating deviations from natural conditions due to human activities, should also include:

- A stakeholder analysis, targeted to the identification of the relevant actors in the issue being studied, and
- Direct engagement and discussion with well owners and farmers to i) tackle the research project more effectively, ii) retrieve reliable information about water and land use, and iii) disseminate the results while performing knowledge exchange on groundwater status and protection strategies.

This newly established field can hence allow hydrogeologists to focus on mutual relations between groundwater and society and to foster both ‘horizontal’ (e.g. between state and non-state actors or across sectors such as agriculture or energy) and ‘vertical’ (between various levels) cooperation (Re, 2015).

STAKEHOLDER NETWORK ANALYSIS

A stakeholder network analysis (SNA) performed at the beginning of any hydrogeological investigation can permit to gain a better understanding of the formal and informal interactions between the different actors (Wasserman and Faust 1994). SNA permits the identification of the most influential stakeholders within a specific network, the analysis of formal and informal interactions among them, and it is considered a particularly powerful tool in natural resource management initiatives seeking to influence stakeholders’ behavior through key individuals (Reed et al. 2009). The Net-Map toolbox (Schiffer and Waale 2008) was identified as the most convenient tool to perform a SNA being easy to understand, flexible, not too time-consuming, and offering the chance to implement preliminary public engagement with limited effort.

Net-Map is an interview-based tool method, facilitating the identification of all the actors involved in a given issue (including marginal ones) while also highlighting their power relations, their influence and their main goals (Schiffer and Waale 2008), by means of the so-called Influence Network Map (INM). Net-Map is a low-cost, easily implementable research tool that aims to make implicit knowledge about networks explicit, hence it is particularly adequate when environmental issues are at stake.

PUBLIC ENGAGEMENT

The overall goal of the public engagement activity is to create momentum of dialogue on local groundwater protection and capacity building, while also collecting relevant information on groundwater use and farmers' perceptions of pollution issues. This activity can allow hydrogeologists to get acquainted with the cause-effect relationship between humans and groundwater, hence to assess not only how human activities can affect groundwater quality and quantity, but also how scarce or polluted groundwater can influence human wellbeing.

Public participation activities can be facilitated by structured interviews administered directly by the research team during *in situ* hydrogeological measurements and sampling collection. The main aim of this activity is therefore to start a dialogue with groundwater end-users (as the basis for participatory management approaches) and to obtain direct and reliable information to support hydrogeochemical data interpretation. The general structured of the proposed questionnaires is reported in Table 1.

Table 1. Summary of the structure and information retrieved with the questionnaires proposed by Re (2015).

Part	Objective	Kind of information retrieved
1. General information	Obtain information (to be treated anonymously) on the rural population features	Gender, age, education, occupation, contacts
2. Water use	Retrieve information on regional and local characteristics to support data interpretation	Well features (age, depth, main characteristics), groundwater abstraction rates, groundwater use, perceived or ascertained groundwater quality issues
3. Purposes of groundwater uses	Obtain information on local activities and priorities to support data interpretation	Groundwater use, kinds of crops cultivated, seasonal production, kind and quantity of fertilizers used, irrigation type
4. Awareness of water issues	Know farmers and well holders perception about local and global water issues	Perception of: water scarcity, climate change, integrated water resources management and groundwater pollution
5. Potential for Participation	Evaluation of the potential for the implementation of participatory monitoring assessments and management initiatives	Farmers' role in groundwater protection, awareness of groundwater issues in the region, perception of scientists and policy makers role with respect to local groundwater management, willingness to be included in the groundwater monitoring network

INSIGHTS FROM A SOCIO-HYDROGEOLOGICAL INVESTIGATION IN THE GROMBALIA BASIN (TUNISIA)

The socio-hydrogeological approach was tested for the first time in the Grombalia Basin (Tunisia), chosen as representative of the issues shared by most of the coastal aquifers in arid/semi-arid regions (i.e., aquifer pollution and salinization, water overexploitation, saline-water intrusion, and agricultural return flow).

The Social Network Analysis performed at the beginning of the investigation (February-March 2014) highlighted the presence of three main group of actors that can positively contribute to the

implementation of new groundwater-based management practices resulting from the hydrogeological investigation (Figure 1):
i) the Groups of Agricultural Development (GDAs; composed by landowners, farmers and water users sharing water resources in each irrigated area, and coordinated by a board of democratically elected local members);
ii) the Regional Commissariat for Agricultural Development (CRDA, i.e. the institution responsible for water resource management and control in the Grombalia region); and
iii) representatives of local farmers (Tringali et al., 2017).

These will be the primary groups results will be shared with, as the most influential stakeholders in the region with regard to groundwater contamination and protection.

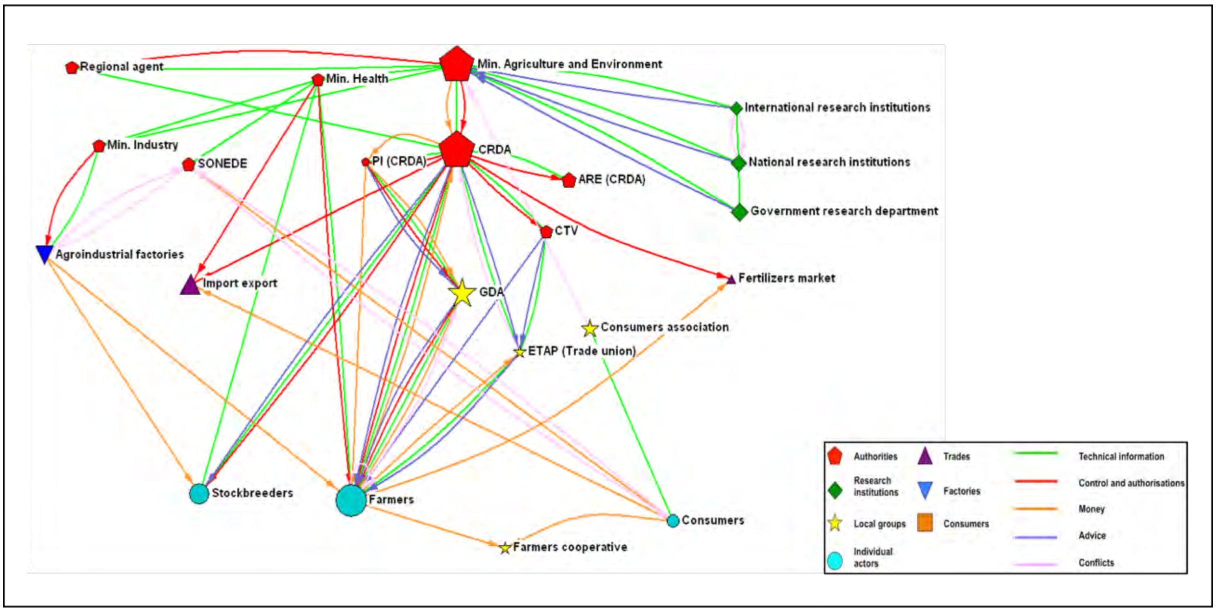

Figure 1. INM for stakeholders involved in groundwater management and protection in the Grombalia basin (Tringali et al., 2017).

Public participation of local actors proved to be a fundamental element for the development of the hydrogeological investigation, as it permitted to obtain relevant information to support hydrogeochemical, isotopic and land use data interpretation, and eventually guaranteed the correct assessment of nitrate contamination sources in the studied area, avoiding the implementation of improper management actions or penalizing farmers (Re et al., 2017).

In particular, interview administration provided useful information supporting the hydrogeochemical analysis, and, as in the case of fertilizers use, in agreement with the findings of the isotopic assessment. Indeed, when budget limitations do not permit a full isotopic assessment, public engagement activities could represent a useful tool to provide insight on possible contamination sources. Coherently, public engagement and capacity building are fundamental to inform farmers and households on the impact of agricultural practices and domestic activities (also with regard to the long-term health and food security implications) as well as to assess their needs and perceptions of environmental issues (Re et al., 2017).

Finally, as concerns the identification of a new and shared strategies for long-term groundwater protection, priority will be given to the identification of new actions that will not compromise the farmer's productivity, and that will take into account the contribution of multiple contamination sources (domestic, urban and agricultural). In this process the role of hydrogeologists and local mediators will also be fundamental to ensure adequate information sharing to the general public and civil society.

ONGOING ACTIVITIES AND FUTURE PERSPECTIVES

Given the positive results of the Tunisian case study implementation, ongoing research relates to the application of the socio-hydrogeological approach in different geographical and socio-economic contexts. Different case studies will be useful to assess the overall validity of the method and to identify the possible criticalities to be assessed.

At present socio-hydrogeology is applied in the framework of the INTEGRON project (funded by the Italian CARIPLO Foundation, Grant number: 2015-0263), targeted to the evaluation of the role of groundwater in contaminants removal and storage in the Po plain region (Italy).

Preliminary results highlight that the complexity of the networks and the emerging multiple perceptions of the hydrogeological problem under investigation, thus, confirming the needs to enforce a holistic approach in groundwater investigations. Public engagement and social network analysis hence result a powerful tool to evaluate the interface between environment and society and to reach a more comprehensive representation of the links and feedbacks between groundwater and human systems (Musacchio et al., 2017).

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DEVELOPMENT OF A FOCUSED INTEGRATED CATCHMENT MANAGEMENT TOOLKIT FOR USE IN SECONDARY SCHOOLS

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ABSTRACT

In Ireland, a number of rivers, lakes and groundwater systems are at risk of pollution both now and in the future. While the role of public engagement in catchment management is becoming increasingly recognised in academic, governmental and social spheres, it is only just beginning to be fully implemented and realised in Ireland. A key gap identified by the 2014 EPA Research Report – Towards Integrated Water Management (TIMe) is a lack of Integrated Catchment Management (ICM) focused primary or secondary school initiatives. Having reviewed best practice in ICM, Environmental Education (EE) and strategies for community engagement and place based learning, this overall project aims to help inform the foundation of ICM by utilising a Participatory Action Research (PAR) approach, that allows for the fostering of a curriculum to combine local knowledge, EE and outdoor field skills with the use of QGIS skills in the classroom. The Uisce Aille project, a pilot program which is funded by the Burren and Cliffs of Moher UNESCO Geopark through the EU LIFE project will result in an educational toolkit that will enable educators to explore an alternative approach to local stakeholder engagement: i.e. train the trainers, to engage the students, so that they can share the message with their local community. Ultimately the program devised will align itself with the execution of the EU Water Framework Directive (WFD) within Ireland: it is participatory, it is educational, it is emancipatory, it is based in and of a community, and the outcomes will be replicable and transferable across the Irish secondary school sector.

Keywords: Environmental Education, Place-based Learning, Educational Toolkit, Integrated Catchment Management, Water Resource Management, GIS, Water Framework Directive.

1. Introduction

The EU Water Framework Directive 2000/60/EC (WFD) ushered in a new perspective on water resources management in Europe. Environmental sustainability is at the core of the directive, and its ultimate successful application requires a shift from *end of pipe* solutions to management of catchments in a systemic, integrated and interdisciplinary way. Catchments are well-connected systems, and *ecological status* is used in the WFD as an indicator of the health of the system. Taking an integrated approach to catchment management requires various disciplines to take a more reflexive approach to collaboration and seeking solutions to complex systems while retaining scientific rigour.

In Ireland, while many of our fresh water resources are in comparatively good overall health, ~47% of rivers and ~57% of lakes are reported as only moderate or worse ecological status, ~1.5% of groundwater resources are classified as being of poor chemical status (an improvement from 14% previously) and ~55% of estuarine and ~7 % of coastal waters are of moderate to bad status (EPA, 2015a). More worryingly, in the case of rivers, only 21 sites were classified as achieving high status in the most recent round of reporting as compared with 575 sites between 1987 and 1990 (EPA, 2016). A widely acknowledged causative factor in the continuing degradation of our water resources is a lack of consciousness and engagement in water protection issues within local stakeholder groups (Daly *et al*., 2013). This has led to a move towards a more comprehensive participatory approach to water management that is beginning to be implemented on a ground up basis (Raadgever *et al*., 2012; Daly *et al*., 2016). The overall aim of the project presented here was to engage with a group of catchment stakeholders in an inclusive way and to sustain that engagement. From a research perspective, the aim was to explore the educational role and effectiveness of a catchment-based curriculum on students in a secondary school setting in the context of engagement and participation. The specific objective was to develop an environmental education resource aimed at secondary level students that will allow them to become familiar with, and map, *their* catchment and its underlying environmental characteristics and structures. To achieve this, the research adopted a Participatory Action Research (PAR) approach, a cycle of action and critical reflection (Cahill, 2007).

2. Legislation Background

In 1992 the International Conference on Water and the Environment (ICWE) in Dublin produced a definitive statement on the emerging water crisis. The message was stark: water is a finite and valuable resource (ICWE, 1992). This was further backed by Agenda 21 at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro later that year, calling all nations to action[1] and the 2002 Johannesburg Implementation Plan on Sustainable Development[2]. Integrated Water Resource Management (IWRM) was derived from the recognition, outlined above, that in a globalised and increasingly crowded world, natural and monetary resources were becoming increasingly limited, and so there was a pressing need to invest in the management and co-ordination of research, protection and sustainable use of water and land at a catchment level, as a fundamental political goal (GWP, 2000). Formal IWRM structures and approaches grew out of the recognition that institutional discordance was rife within the water sectors of most nations, with often conflicting policies that impede the central goal of protecting healthy water systems (Forslund *et al*., 2009).

The Global Water Partnership (GWP) definition of IWRM, which informs Ireland's Environmental Protection Agency's water integration manifesto is *'a process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems'* (EPA, 2017). A principle concept of the ICWE in Dublin was the recognition of the *Participatory Approach: Local communities must help make decisions about their resources* (ICWE, 1992).

[1] https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf
[2] http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf

Table 1: Other drivers of Integrated Water Resource Management (IWRM)

Other Drivers of IWRM – • European Communities (Water Policy) Regulations, 2003 (S.I. No. 722 of 2003) • Water Services Amendment Act (SI No 2 of 2012) • Urban Waste Water Treatment Directive (91/271/EEC) • Bathing Water Directive (2006/7/EC) • Drinking Water Directive (98/83/EC) • Habitats Directive (92/43/EEC) • Nitrates Directive (91/676/EEC), aims to protect water quality from contamination by agricultural sources and also to promote good farming practice. • **Ireland's Environment Report** highlights the need to achieve good-quality water through appropriate management[3]. • **UN Millennium Goals**[4] • **2020 Vision: Protecting and Improving Ireland's Environment -** outlines Protected Water Resources as one of the main environmental goals for Ireland, along with five other areas across a broad spectrum[5]. • **The Water JPI on "Water challenges for a changing world"** emphasizes the importance of stakeholder engagement in addressing safe and sustainable water resources[6]. • **National Nitrates Action Programmes NAP** – 1)a limit on the amount of livestock manure applied to the land each year; 2) set periods when land spreading is prohibited due to risk; 3) set capacity levels for the storage of livestock manure[7] • **Food Harvest 2020**[8]

3. Integrated Catchment Management

Integrated Catchment Management (ICM), both as a subset of IWRM and as a stand-alone concept, is an approach that distinguishes the catchment as the proper landscape unit within which to organise and manage all ecological, social and economic processes through sustainable policy and action (Rolston *et al.*, 2014). The WFD is the catalyst for the catchment based approach in the protection, preservation and improvement of water environments, encouraging local community engagement, particularly at the subcatchment level (DEFRA, 2013). Since its adoption in 2003 Ireland's approach to implementation has evolved. The initial setting up of seven River Basin Districts (RBDs) saw consultants, local authorities and public bodies work together to characterise Ireland's water resources and the stresses upon them resulting in river basin management plans (RBMPs) and improved monitoring (Daly *et al.*, 2016). Daly *et al.* (2014) outline the successes of the first round of RMBPs as well as a number of flaws including insufficient public and community engagement. The second cycle RMBP will see the Eastern, South Eastern, South Western, Western and Shannon River Basin Districts (RBDs) merged into one national RBD and will also see a new course for implementation of the WFD with a clear three tier governance hierarchy[9]:

[3] http://www.epa.ie/irelandsenvironment/stateoftheenvironmentreport/
[4] http://www.un.org/millenniumgoals/
[5] http://www.epa.ie/htmldocs/2020Visioneng/2020Vision.htm
[6] http://www.waterjpi.eu/
[7]https://www.agriculture.gov.ie/ruralenvironment/environmentalobligations/nitrates/nitratesactionprogramme-consultationpaper/
[8]https://www.agriculture.gov.ie/publications/2011/annualreviewandoutlookforagriculturefisheriesandfood20102011/nationaldevelopments/foodharvest2020/
[9] http://www.epa.ie/water/watmg/wfd/wfdgovernance/

Table 2: Three tier governance hierarchy for implementation of Integrated Catchment Management in Ireland, (adapted from Rolston *et al*., 2014)

Tier 1 - National Management and Oversight: Led by the department of Housing, Planning, Community and Local Government dealing with policy, regulation and resources; and responsible for sign-off of RBMPs.
Tier 2 - National Technical Implementation and Reporting: Led by the EPA responsibility for water monitoring, assessment, characterisation, identification of measures and reporting to the European Commission, as well as licensing of discharges and monitoring of enforcement tasks and environmental outcomes.
Tier 3 - Regional Implementation via Water Networks: led by the Local Authority Waters and Community Office (LAWCO) in co-operation with local authorities (LA). To coordinate Local Authorities through agreed regional structures, thereby providing a collaborative approach to river catchment management and to engage local communities and promote public participation in the management of the water environment[10]

ICM is strongly rooted in the triple ethos of sustainability, the idea that truly insightful and satisfactory policy is born when one hits upon the correct equilibrium between economic, social and environmental considerations. This ethos is reflected in recent work on the state of the WFD and on ideas of social geology. Both Daly *et al.* (2016) and Voulvoulis *et al.* (2017) stress the importance of meaningful and sustained stakeholder engagement in the success of the next phase of the WFD. Stewart and Gill (2017) argue convincingly for the inclusion of ideas of sustainability into both geoscience education *and* practice. Daly *et al*. (2016) stress that the success of the next phase of the WFD requires a paradigm shift in approach and thinking and that stakeholder engagement is key to this. The ICM concept suggests a vigorous structure for improved resource management, while refining and opening up the silo based approach to catchment management that characterised the first phase of the WFD in Ireland; Daly *et al.* (2016) argue that while the move away from an entirely silo based system is essential, there are a number of practical and achievable suggestions to overcome the disadvantages while retaining the various expertises and working together. ICM will be most successful where policy shows true assimilation of all decision making processes (Lerner & Zheng, 2011). Public policies may be 'procedural, substantive, symbolic or instrumental' according to Sabatier (2007). They are developed both as a mission statement to focus objectives and as a missive to communicate those objectives. In the case of the WFD, it is the RBMPs and their implementation that outline a clear ambitious blueprint to embedding the concept of ICM at the heart of water management across the entire EU (Voulvoulis *et al*., 2017).

Daly *et al.* (2017) suggest that full engagement with, and of, and retention of stakeholders is the greatest challenge to the success of ICM in the WFD context. A social learning approach is suggested to address this challenge, echoing Stewart and Gill's (2017) call for geoscientists to rethink how they operate in the public arena. There are well established social science models that are readily applicable, the most obvious being Bronfenbrenner's (1979) ecological model. His approach to assessing human behaviour focuses not only on the individual, but on the interactions of the individual, the society within which the individual lives, the larger legal and social framework, and time. His approach provides a useful structural guide to ICM in that it requires an understanding of the various layers and levels at play in a catchment. This includes the idea that new systems and interactions may develop in future and the approach stresses that there has to be enough flexibility to allow for systems and interactions between those systems. He suggests a way of assessing all of the influences on human behaviour by exploring at all aspects from the interpersonal level to community level to the legislative level which provides a useful framework for ICM.

This gives a more holistic insight into how a catchment functions, socially, economically and ultimately environmentally. This approach was adopted by the Hydrology for the Environment, Life and Policy (HELP) joint initiative of United Nations Educational, Scientific and Cultural Organization

[10] http://watersandcommunities.ie/about/

(UNESCO) and the International Hydrological Programme (IHP) which sought to a science-based method to catchment management that could foster an exchange of ideas between scientists, local stakeholders and policy makers (Falkenmark, 2004).

Daly *et al.*, (2016) see ICM as a new type of *reflexive* governance – open, experimental and learning oriented - that while building on the past provides an 'organising framework', allowing us to view catchments in their full four-dimensional reality (including *time*) at a scale that allows sovereignty of all stakeholders through true citizen engagement . However, the approach only works where there is true integration at all levels: de Loë *et al.* (2016) stress the importance, in this context, of stakeholders "*as knowledge generators not just knowledge recipients*" (de Loë *et al.*, 2016). It is within the above national context that the new Catchment Science and Management Unit of the EPA[11] and the new catchments website[12] sit.

4. Catchment Management Programmes within Ireland

A number of local, bottom-up catchment management projects have started in recent years in Ireland (*Table 3*).

Table 3. Summary of catchment management initiatives in Ireland

Lough Leane Project	1998 – 2001: In response to an algal bloom on Lough Leane, Cost of £1 million **(DELG, 2013)**
Lough Derg and Lough Ree	1997 – 2000: To reduce Phosphorous inputs to rivers and lakes, Cost of £2.3 million[13].
Burrishoole Catchment	1950s – present: Long term data collection, multiple funding sources[14].
Lough Melvin Agri-Environmental Program	2005 – 2008: Increased Phosphorous levels, Cost of ~ €974000 **(Girvan and Foy, 2003)**.
Three Rivers Project	To develop catchment based water quality and management systems to avoid deterioration in water quality[15].
Ann Valley Project	Catchment restoration project, wetland construction **(Harrington *et al.*, 2004)**.
Pathways Project	To develop a catchment management tool and hydrological conceptual flow model to ensure good water body status. Led to development of national Pollution Impact Potential (PIP) tool **(Archibold *et al.*, 2010)**.
Agricultural Catchments Programme	6 catchments identified and monitored for changes in water condition due to nutrient transfer **(Teagasc, 2003)**.
Catchment Flood Risk Assessment and Management CFRAM	Preparation of preliminary and final flood maps to inform a national Flood Risk Management Plan[16].
Burren LIFE	Develop a new model of reward for sustainable farming for conservation[17].
Mulkear LIFE	Restoration of the Lower Shannon habitat for Sea lamprey, Atlantic Salmon and Otter[18].
Raptor LIFE	Connect and restore habitats for Hen Harrier, Merlin, Atlantic Salmon and Brook Lamprey[19].

[11] http://www.epa.ie/water/watmg/icm/
[12] https://www.catchments.ie/
[13] http://www.epa.ie/licences/lic_eDMS/090151b28024fccc.pdf
[14] http://burrishoole.marine.ie/
[15] http://www.epa.ie/licences/lic_eDMS/090151b280249632.pdf
[16] https://www.cfram.ie/
[17] http://burrenprogramme.com/category/farming/
[18] http://mulkearlife.com/

Kerry LIFE	Conservation of rivers Caragh and Blackwater in County Kerry habitats and species including the freshwater pearl species[20].
Duhallow LIFE	Conservation of habitat, restoration of channels and curbing the spread of invasive species[21].
Aran LIFE (Aranlife.com, 2017)	Supporting sustainable and traditional farm management practices on the Aran Islands[22].
StreamScapes	Primary school focused integrated catchment management program designed to promote local rivers and important wildlife habitats **(Boyden, 2015)**.
Rivers Trusts	River Blackwater Catchment trust (Cross border); Erne Rivers Trust (Cross border); Slaney Rivers Trust; Nore Rivers Trust; Inishowen Rivers Trust; Maigue Rivers Trust; Waterville Rivers Trust; and River Moy Rivers Trust[23].
Our Community, Our Water	New project run by Dundalk IT aimed at local communities [24]

To date only one dedicated catchment management education programme which is in operation across Ireland, albeit with a primary school focused programme. Even with the success of this innovative aquatic and biodiversity primary schools programme (Boyden, 2015), the of lack of ICM focused primary *or* secondary school initiatives was identified as a major educational gap (Rolston, *et al*., 2014). The project outlined here will help to close that gap, by developing a focused ICM toolkit for use in secondary schools encompassing public outreach, citizen science and use of GIS mapping techniques.

5. Project Aims

This project is two-part resource management undertaking, focusing on the efficacy of integrated catchment management, with the following aims and objectives:

- Aims
    - To develop a **robust tool** for educational purposes which a secondary school setting that can be adapted and utilized for engaging a wider community; and,
    - To rigorously and academically **appraise the ICM process** in the context of educational involvement, through participatory action research.
- **Goals:**
    - To inform future catchment management decisions and policies;
    - To highlight the importance of engagement with and sustaining of the local community;
    - To stress the significance of early environmental education; and,
    - To facilitate the spread of knowledge in an engaging, modern way.

The curriculum aims to channel students' energy into positive action, empowering them to develop a stewardship of their local water resources. It is being designed, with student input, as a transferable toolkit that can be used in any secondary school as (ideally) a transition year (TY) project that can run

[19] https://www.duhallowlife.com
[20] http://kerrylife.ie/
[21] https://www.duhallowlife.com/
[22] https://www.aranlife.ie/
[23] http://www.theriverstrust.org/2017/03/24/rivers-trusts-across-ireland/
[24] http://talkofthetown.ie/tag/suzanne-linnane/

over several months. It is being designed to allow the students to take the lead on the project and to provide online and technical resources to facilitate the project. This is a three-step process (Figure 1).

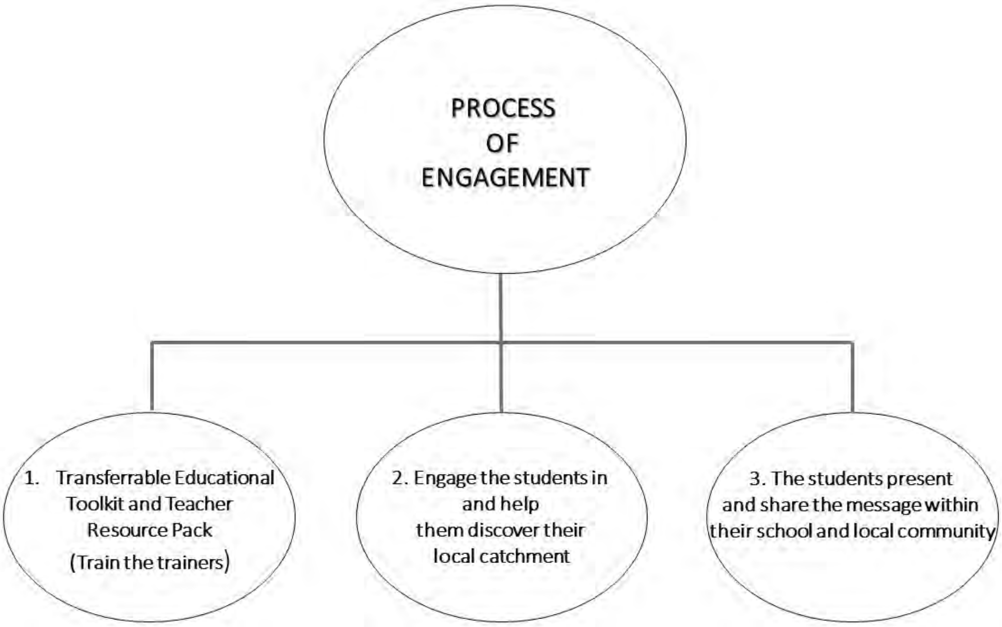

Figure 1. Three Step Process of Engagement

6. Methodology

A PAR approach has been utilised as it is also an effective method that allows for an adaptive working process, facilitating inclusion and social engagement (Bracken *et al.*, 2015). Based upon this structure, the research is being completed with a TY class (ages 15 to 16) of 19 students from a state secondary school in County Clare. In this pilot programme, the students have been exploring and mapping the natural and built environment underlying the Aille river catchment in the Burren. Part of this pilot project, *Uisce Aille*, incorporates place-based outdoor environmental education (EE) by taking the students to reaches of the river to learn various field sampling and data recovery skills, introducing them to the concept and the practice of citizen science. Students have also been introduced to the wealth of freely available environmental information online and receive comprehensive QGIS training, an Open Source Geographical Information System (GIS)[25].

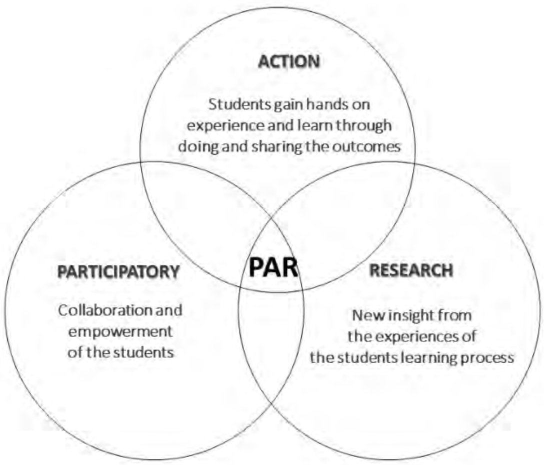

Figure 2. PAR Venn diagram (adapted from Chevalier and Buckles (2013)

[25] http://www.qgis.org/en/site/about/index.html

7. Outcomes

Assessment of cognitive outcomes can be difficult in these types of projects, but the impact of the student *affective* domain (Boyle *et al.*, 2007) is clear: the students have grown in confidence in their abilities to collect and represent data and to present this data in map form and in public presentations. The students recently presented their findings to more than 100 representatives from various European Geoparks at the 39th Coordination Committee Meeting held in the Burren in March 2017. The students also submitted an entry for the ECO-UNESCO Young Environmentalists Awards. This activity sought to focus the students and allowed the researcher to assess the learning process. In broad terms, outcomes were assessed using quantitative instruments in a quasi-experimental setting. Meyer and Land (2003) proposed the idea that in certain disciplines there are conceptual gateways (*thresholds*) that lead to a previously inaccessible, and initially perhaps troublesome, way of thinking. A new way of understanding, interpreting, or viewing something may thus emerge – a transformed internal view of subject matter, subject landscape, or even world view. Characterising these *threshold concepts*, Meyer and Land (2003) suggested that they may be transformative (occasioning a significant shift in the perception of a subject), irreversible (unlikely to be forgotten, or unlearned only through considerable effort), and integrative (exposing the previously hidden interrelatedness of something). Within the context of the approach embedded in the WFD the idea of threshold concepts, applied to integrated catchment management and to ecological status, makes perfect sense and provides a theoretical rationale and basis for approaching complex environmental management issues. In the context of this study, the students have crossed a threshold in their understanding of the catchment within which they live, and this new perspective has given them a broader sense of belonging and ownership of their shared water resource.

8. Conclusion

Educational theorists have long reported on the efficacy of place based education (Kent, 2014; Pike, 2011). This study presents a new pedagogical idea and practice for educational practitioners within the secondary school cycle. The students underwent a 14-week study programme focused on outdoor field work, GIS mapping, catchment walks, guest speakers from local organisations and public bodies and personal learning in the form of the YEA entry. Sitting as a multi-disciplinary project, the ICM toolkit fits within the current Leaving Certificate Geography, Biology and IT curriculum. The place-based nature of the program grounds the students learning in their own landscape, community and shared history, thereby enhancing the experience.

This model of ICM education aims to encourage a community to take responsibility for their shared resources and to become even more aware of the link between water, the natural and built environment, and the population using and dependent upon it - in the past, present and future (Bowden *et al.*, 2004). As it is widely becoming evident that top down mandates can only be successful with the help and stewardship of local communities, it is anticipated that the curriculum and accompanying teacher resource guide will sit within an ICM ethos, being participatory, educational, and emancipatory. By encouraging awareness, pride, and participation through training future local stakeholders, it is hoped that this program may be a stepping stone to the formation of a local River Trust in the area. Future research will involve rolling out the curriculum in other schools throughout west of Ireland to investigate the replicability and transferability of the programme.

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A SENSITIVITY ANALYSIS IN RELATION TO CLIMATE CHANGE IMPACTS ON GROUNDWATER RECHARGE TO IRISH FRACTURED-BEDROCK AQUIFERS

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ABSTRACT

Water resources are potentially vulnerable to climate change as a consequence of an intensification of the hydrological cycle. However, it is also known that the magnitude of the possible impacts is strongly dependent on specific catchment characteristics. A sensitivity analysis has been carried out for three Irish catchments with different hydrogeological settings to determine how bedrock properties control recharge in Irish low-storativity aquifers, and to assess the possible impacts of climate change. This paper presents the sensitivity analysis for one catchment; this included meteorological variables such as rainfall amount, its intensity and seasonality, and also the hydrogeological variables controlling actual recharge. The results to date suggest that the effect of changes in climatic variables is strongly influenced by the local hydrogeological settings. This would lead to an unequal impact of climate change across the country depending on the local settings.

INTRODUCTION

In Ireland, a methodology has been developed for quantifying recharge using geological and hydrological information contained in a Geographical Information System (GIS) (Fitzsimons and Misstear, 2006*;* Misstear *et al.*, 2009a,b*;* Hunter Williams *et al.*; 2013). Firstly, the hydrologically-effective rainfall is calculated using a soil moisture budget approach. Then a recharge coefficient is applied which determines the proportion of the effective rainfall that becomes potential recharge. The main factors influencing the recharge coefficient are the permeability and thickness of the subsoils; the drainage characteristics of the topsoils, the presence of peat deposits, and the presence of karst features. The potential recharge is then adjusted by taking account of the ability of the aquifer to accept groundwater recharge. For aquifers classified as being poorly productive (PPAs), recharge caps of 100 mm/y or 200 mm/y are applied depending on the sub-category of aquifer.

This methodology has proven very useful for providing preliminary estimates of groundwater recharge in river basins across the country. However, further research is now needed on how the specific properties of the bedrock aquifers affect their ability to accept recharge. In addition, in the context of a changing climate, changes in precipitation distribution, amounts and intensity are anticipated. Whilst climate change projections are uncertain, there is wide agreement in the prediction of an intensification of the hydrological cycle (Bates *et al*., 2008; Gleeson *et al*., 2013) which would lead to longer and drier summers, and an increase of high intensity rainfall causing flooding. This alteration of the hydrological cycle points at possible reductions in groundwater recharge (Sweeney *et al*., 2008; Gleeson *et al*., 2013).

In this research, the GIS recharge tool is used in combination with soil moisture budgeting techniques to characterize groundwater recharge in three selected catchments, and to perform a sensitivity analysis. The variables examined include hydrogeological and meteorological factors.

SELECTED STUDY AREAS

Three Irish catchments with contrasting hydrogeological and climate properties were selected for the sensitivity analysis: the Mattock (Co. Louth), Nuenna (Co. Kilkenny) and Dripsey (Co.Cork). However, only the results obtained for the Nuenna catchment are presented in this short paper.

The Nuenna is a tributary of the River Nore and has an approximate catchment area of 35 km^2. The main land use in the catchment is pasture and the dominant subsoils are sands and gravels and permeable tills. Regarding the bedrock composition, the majority of the area is underlain by Dinantian limestones, which are classified as regionally important aquifers. The borders of the catchment, which also correspond to the higher areas, are composed by Namurian shales which are regarded as poorly productive aquifers. A recharge cap of 100 mm/y is applied in these areas.

METHODOLOGY

The research presented here aims to improve our understanding of the controls exerted by hydrogeological and meteorological variables on groundwater recharge. This would allow us to identify the variables that have a larger effect on recharge and therefore to identify those areas more susceptible to climate change. To do so, a sensitivity analysis has been carried out for the three study catchments.

The GIS-based tool has been used to calculate both the current recharge and to perform the sensitivity analysis. The tests performed include relevant hydrogeological features of the catchments but also anticipated changes in rainfall patterns such as intensity and seasonality (Table 1). In the sensitivity analysis a variable is modified whilst fixing the other variables, so as to be able to determine how it constrains groundwater recharge. The larger the variation, the greater is the sensitivity to the studied variable.

Rainfall rates	Recharge coefficients
Rainfall intensity	Recharge caps
Rainfall seasonality	
PET methods	
AE rates	

Table 1: List of variables included in the sensitivity analysis for potential and actual recharge

HYDROGEOLOGICAL VARIABLES

First of all, research was carried out to determine suitable ranges in which to alter the recharge coefficients and caps. The best estimates for the recharge coefficients were established in Hunter Williams *et al*. (2013) when the national recharge map was developed. This followed earlier work describing the results of recharge estimations and recharge coefficients in four study catchments (Misstear *et al*., 2009). In these papers, however, a likely range of coefficients is presented for each hydrogeological setting: there are the minimum and maximum values, which are intended as the lower and upper bounds of credible values, and the two inner range limit values. In this sensitivity analysis, these four sets of coefficients have been used to generate four alternative recharge scenarios. Regarding the recharge caps, it was decided to modify the values by decreasing and increasing the values of the recharge caps by 50 mm/y and 25 mm/y.

CLIMATE VARIABLES

Climate projections for rainfall anticipate an increase in rainfall intensity and also an amplification of seasonality (Gleeson *et al*., 2013). For this reason, groundwater recharge sensitivity to these variables has been investigated. To do so, daily series of historical rainfall and potential evapotranspiration (PE) were obtained from Met Éireann for a period of 30 years (1985-2015). Precipitation series were taken from the closest rainfall station with available data over this period. Similarly, potential evapotranspiration data were obtained from the closest synoptic station to each one of the catchments.

To summarize, lumped daily rainfall data and PE estimations have been used as input. Actual evapotranspiration (AE) estimations have been calculated by a soil moisture budget approach, following the recommendations of the Food and Agriculture Organization of the United Nations (FAO) (Allen *et al*., 1998), and combining it with land use information from the Environmental Protection Agency (EPA), so that AE estimations can be distributed across the catchments. This made it possible to also calculate effective rainfall in a distributed way and use it as an input for the GIS tool (Figure 1).

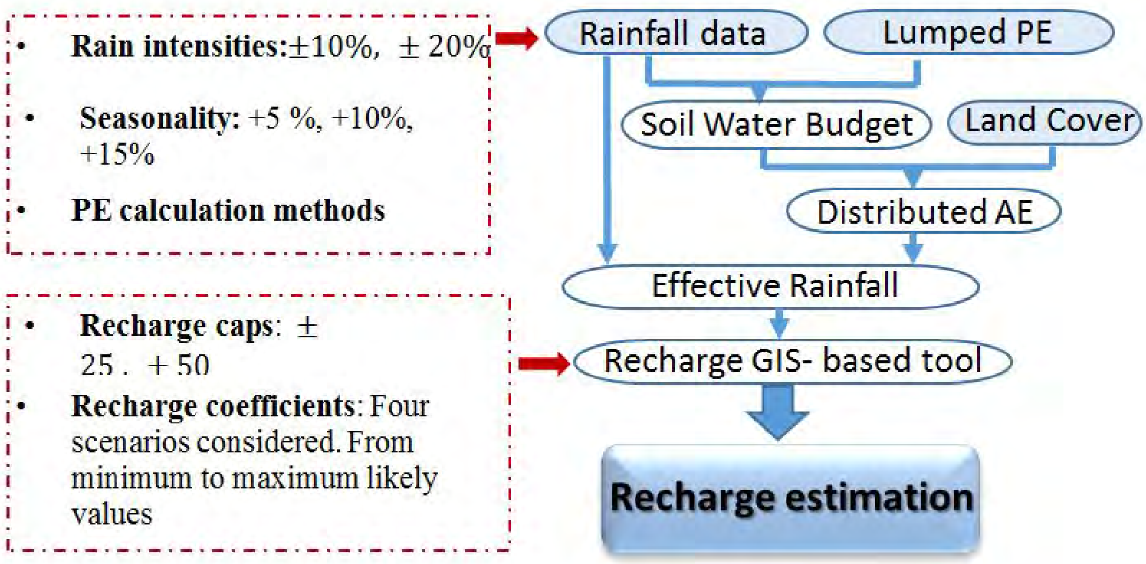

Figure 1: Flow chart of the methodology applied in the sensitivity analysis.

The manipulation of the daily rainfall series has been carried out with the statistical downscaling method, decision centric (SDSM-DC) software (Wilby *et al*., 2002).

INTERIM RESULTS

HYDROGEOLOGICAL VARIABLES

Recharge coefficients

The ranges of likely recharge coefficients values presented by Hunter Williams *et al*. (2013) were used to generate four new recharge scenarios. As expected, the results show a direct relationship between the recharge coefficients and groundwater recharge: the higher the coefficients, the higher the recharge (Figure 2).

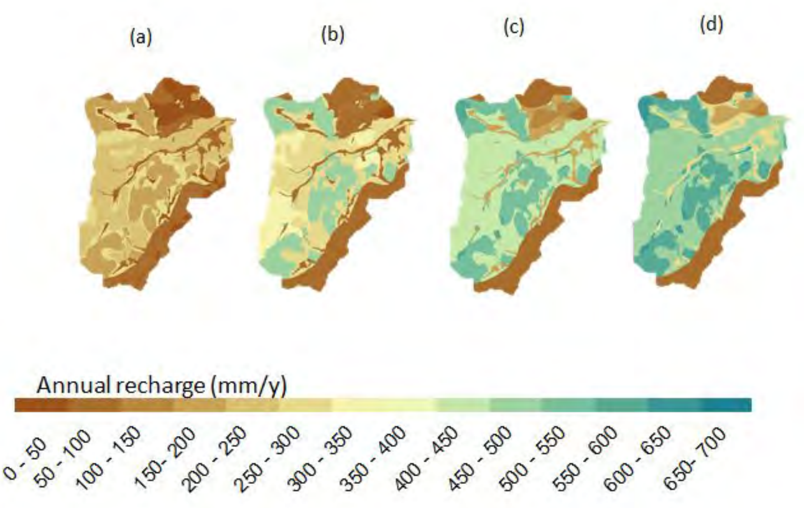

Figure 2: Recharge scenarios in the Nuenna catchment generated from the five recharge coefficient sets: (a) Minimum (b) Lower inner range (c) Original values (d) Higher inner range (e) Maximum

It can also be seen that some areas are more sensitive than others: High sensitivity areas correspond to those zones with high recharge rates, either because the infiltration rates are high, or because they are not affected by recharge caps. In fact, the results also suggest that the less sensitive areas are those corresponding to poorly productive aquifers, since recharge does not increase in these areas once the threshold set by the cap is exceeded.

Recharge caps

The recharge cap values have been modified to increase and decrease the storage capacity of the aquifers by 50 mm/y and 25 mm/y. The first thing that can be observed in the output maps is that only the areas that are underline by PPAs are sensitive to these changes (Figure 3).

Again a direct relationship between the input variable and the output can be observed: the higher the caps, the higher the annual recharge. In addition, the maximum difference in recharge for each scenario is equal to the change applied to the cap values.

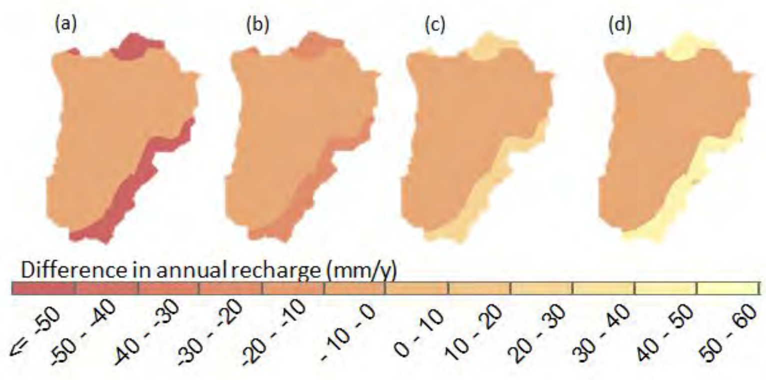

Figure 3: Difference in annual recharge for the four scenarios generated from (a) Low cap values (b) Medium-Low cap values, (c) Medium-High cap values and (d) High cap values

HYDROMETEOROLOGICAL VARIABLES

Historical precipitation data have been obtained for the nearest rainfall station from Met Éireann. In cases of long data gaps, they have been infilled with data from the closest rainfall station. A linear regression between both stations is calculated to obtain a correction factor, which is then applied when there are missing data.

Rainfall intensity

The modification of the rainfall series has been achieved by preserving the annual totals and altering the percentage of occurrence of rain days. The addition and removal of rain days is done by a stochastic forcing, which is randomly based on the likelihood of events occurring in each month. In this way, wetter months have a greater chance to have a rainy day added and *vice versa*. The increment of intensity is done by removing wet days while fixing the annual average so the intensity of the remaining days needs to be higher in order to preserve the total. Four new precipitation scenarios have been generated: two in which rainfall intensity has been incremented by 10% and 20%, and two more in which the intensity has been reduced by the same percentages.

When looking at the effects of changing rainfall intensity on the soil moisture budget, it appears that potential recharge is more sensitive to changes in rainfall intensity than actual evapotranspiration (AE), and presents a more acute seasonality (Figure 4).

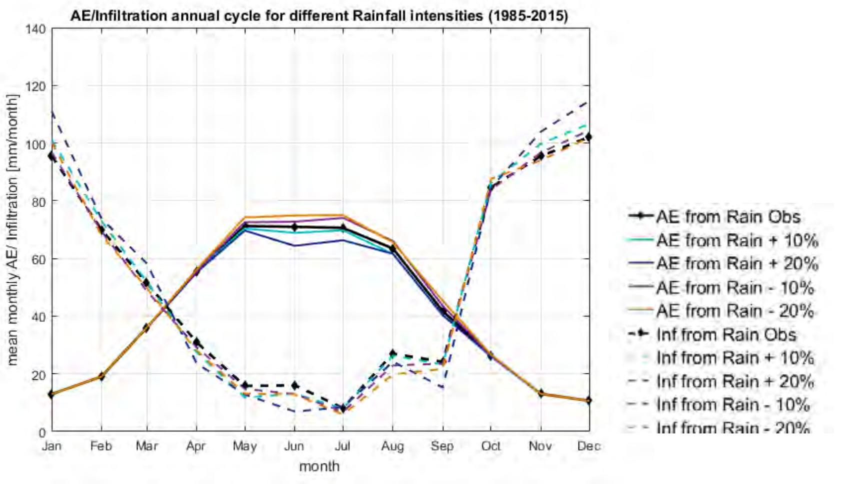

Figure 4 : Actual evapotranspiration (solid lines) and infiltration (dashed lines) annual cycle for the Nuenna catchment (1985-2015) calculated from five rainfall intensity scenarios: Observations (black), 10 % increase (light blue), 20% increase (dark blue), 10% decrease (purple), and 20 % decrease (orange)

Regarding groundwater recharge, the results show that an increase in rainfall intensity leads to a rise in recharge owing to a reduction in actual evapotranspiration (Figure 5).

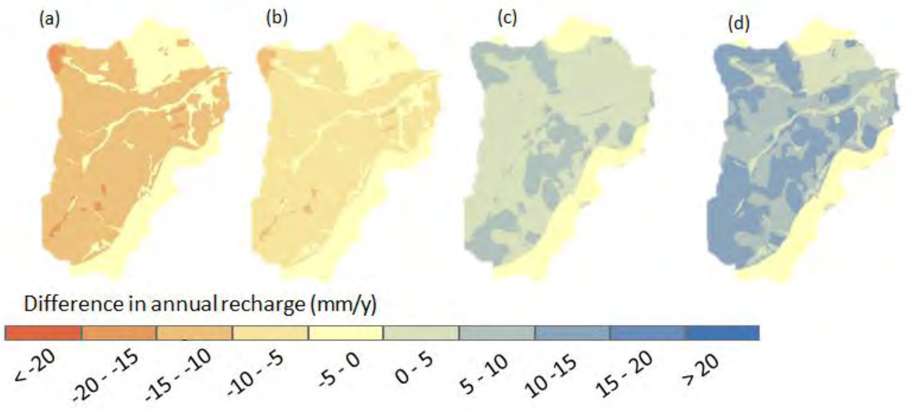

Figure 5: Difference in annual recharge for the four scenarios generated by modifying precipitation intensity in (a) a 20 % decrease (b) 10% decrease, (c) 10% increase, (d) 20% increase

It can also be observed that the effect of changing rainfall intensity is most marked in areas with high recharge coefficients and which are not affected by the recharge caps. On the other hand, the areas underlain by poorly productive aquifers show little variation with changes in rainfall intensity.

Rainfall seasonality
The alteration of the rainfall seasonality was performed in a similar manner to that presented above for rainfall intensity: by fixing the annual averages, then increasing the number of wet-days for the winter months (December, January and February), and reducing the number in the summer months (June, July and August), by a set percentage in each case (Figure 6).

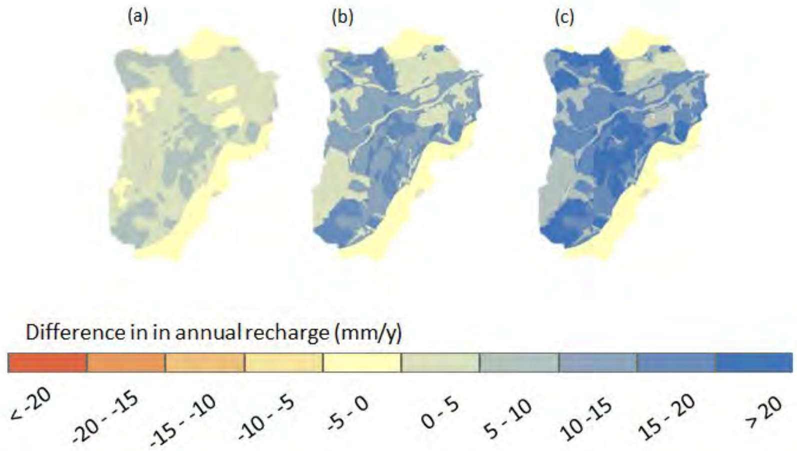

Figure 6: Difference in annual recharge for the three scenarios generated by amplifying seasonality in (a) 5%, (b) 10% and (c) 15%.

The results obtained show that, similarly to rainfall intensity variations, an amplification of rainfall seasonality would lead to an increase of annual recharge due to a significant rise of recharge during winter. However, there is a reduction in recharge during summer months as a result of an enhancement of soil moisture deficit. Nevertheless, the increase projected for the winter months would counteract the reduction in summer, thereby increasing the annual values.

INTERIM CONCLUSIONS

The sensitivity analysis has investigated the effect of changes in the hydrogeological and hydrometeorological variables that control groundwater recharge in the Nuenna catchment. The results suggest that any increases in rainfall intensity or seasonality would lead to an increase of annual recharge due to a reduction in actual evapotranspiration. In addition, the effect of changing rainfall intensity or seasonality is most marked in areas with high recharge coefficients and which are not affected by recharge caps.

The extent of the effect of changes in rainfall intensity and seasonality is strongly influenced by the local hydrogeological settings. This would lead to an unequal impact around the country, owing to the heterogeneous nature of the hydrogeology. These findings are therefore useful for identifying the most sensitive areas and thus setting a framework for the future work.

Future work will focus on characterizing fractured-bedrock aquifers to improve the understanding of the parameters limiting groundwater recharge within these types of aquifers. The findings will be then used in combination with climate projections to assess the possible impacts of climate change on Irish groundwater resources.

ACKNOWLEDGEMENTS

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DYE TRACING GROUNDWATER IN THE RATHCROGHAN UPLANDS, COUNTY ROSCOMMON

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Produced with the permission of the Director of the Geological Survey Ireland

ABSTRACT

The Rathcroghan Uplands in County Roscommon is a karst plateau (ca. 100 km^2) characterised by few surface-watercourses and a high density of karst features such as swallow holes and turloughs, with springs dotted around the lower-lying perimeter. Several of the springs supply drinking water to public and group water schemes. Contamination of these springs is relatively common, and severe pollution incidents have occurred in recent years.

Groundwater behaviour in karst areas, particularly the direction of groundwater flow, is unpredictable. Dye tracing is one of the most important tools available to investigate groundwater flow directions in such terrain. In collaboration with the National Federation of Group Water Schemes, dye tracing investigations were carried out in 2015 and 2016 on and around the Rathcroghan Uplands. The results chart an intricate subsurface network of groundwater flow. This work has added to the conceptual understanding of the karst hydrogeology of the Rathcroghan Uplands and enabled geo-scientifically robust catchment areas to be defined for all of the water supply springs.

PROJECT SCOPE

In order to protect the quality of the water scheme supplies, it is important to establish the surface and subsurface catchment areas, or 'Zones of Contribution' (ZOC), within in which rainfall and potential contaminants may enter groundwater and move towards the supply. These ZOCs provide an area in which to focus further investigation and implement protective measures to manage the groundwater quality and sustainable abstraction rates.

Previous studies (Lee *et al.*, 2003; Drew, 2005; Meehan *et al.*, 2015; Kelly *et al.*, 2015 provide Zones of Contribution for these schemes. These studies were completed for the Public Water Schemes (GWSs) and Group Water Schemes (GWSs) themselves, and are based to a certain extent on topography and historical tracer testing. One of the assumptions made in understanding groundwater behaviour in the region is that the Rathcroghan Uplands is both a surface water divide and a groundwater divide (Hickey, 2009) with groundwater flow directions expected to follow the topography.

The Geological Survey Ireland, in collaboration with the National Federation of Group Water Schemes, set about to further characterise the groundwater regime within the Rathcroghan Uplands. The aim was to delineate individual group water scheme's Zones of Contribution, using hydrogeological mapping and dye tracing techniques.

PHYSICAL SETTING AND HYDROGEOLOGICAL CHARACTERISTICS

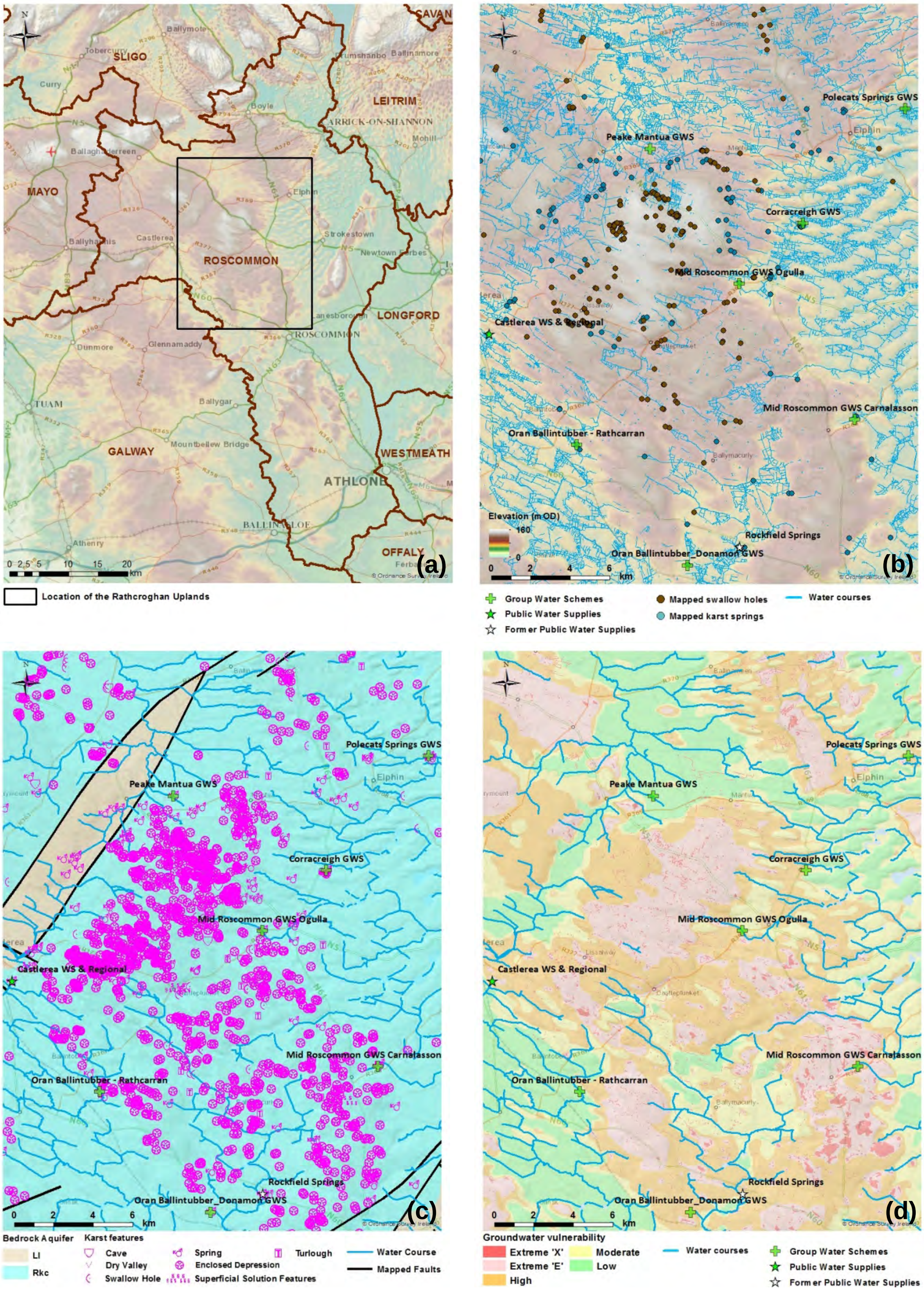

Figure 2 (a) Location, (b) hydrological setting, (c) aquifer category and karst features, and (d) groundwater vulnerability of the Rathcroghan Uplands, County Roscommon

The Rathcroghan Uplands (Figure 1a) is a relatively high karst plateau (ca. 100km^2) located in central County Roscommon, with elevations ranging between 40 - 150 m above sea level. The uplands generally receive around 800 mm of rainfall per year. There is a low density network of surface water courses on the plateau; run-off either enters the subsurface *via* a series of swallow holes fed by sinking streams and reappears at the surface *via* a number of springs at the base, or enters water courses that flow off the uplands. Several of these larger springs provide water to group and public water schemes including Polecats GWS, Peake-Mantua GWS, Corracreigh GWS, Mid-Roscommon GWS, Oran-Ballintubber GWS and Castlerea PWS (Figure 1b).

The bedrock geology consists predominantly of undifferentiated Viséan, pure, bedded, karstified limestone which is categorised as a Regionally Important Karst Aquifer dominated by conduit flow (Rk^c) (Figure 1c). Numerous karst features, including dolines, swallow holes, turloughs, and sinking streams, have been mapped mostly through detailed field work (Hickey, 2009). Bedrock is generally close to the surface across the plateau and the main structural trend is southwest to northeast. Deep, mineral, poorly drained, ('wet') soils are the dominant soil type across the upland area, and several pockets of cutover peat and lacustrine clay also occur. Glacial till ('boulder clay') deposits are the predominant subsoil type.

The consequence of possessing these properties is that the majority of the Rathcroghan Uplands is mapped having "High" and "Extreme" groundwater vulnerability (Figure 1d). Groundwater vulnerability is generally mapped as 'Extreme' across the majority of the area of the Rathcroghan Uplands, where bedrock is often close to surface and karst features (swallow holes, enclosed depressions and sinking streams) are present in abundance. In the northwest area of the plateau (where low permeability till is present) and the central area of the plateau (where drumlins occur) the groundwater vulnerability is mapped as 'High'. Generally off the plateau and on the lower ground, 'Low' groundwater vulnerability is mapped due to the presence of thicker, 'low' permeability subsoil.

Figure 2 shows a conceptual model of the hydrogeological characteristics of Mid Roscommon (Ogulla) Group Water Scheme (Meehan, *et al.*, 2015), basing the groundwater flows on hydrogeological mapping and tracer testing.

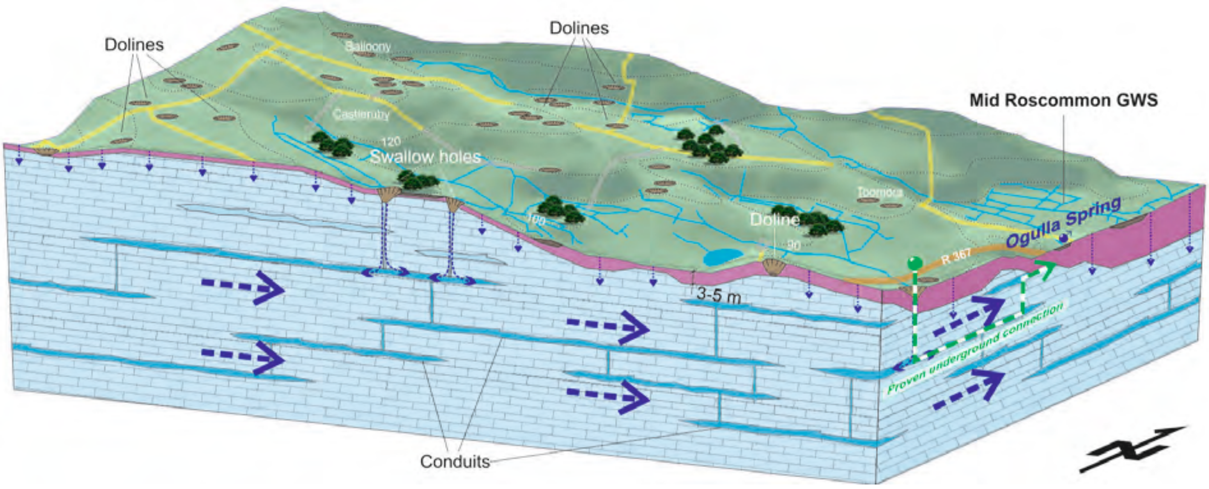

Figure 3 Cross section through Rathcroghan Uplands showing the conceptual model of the Zone of Contribution to the Mid Roscommon (Ogulla) GWS spring source, from Meehan *et al.*, 2015

METHODOLOGY - TRACING PROGRAMME

The tracing was conducted in May and August of 2015, and June, July and October 2016, from a total of thirteen swallow holes. Summary details including dye types and amounts used are provided in Table 1. The sampling strategy included the selection of suitable outlets where the dyes might appear, selecting the appropriate sampling frequency for each one, and mobilisation of equipment. This was completed according to Geological Survey Ireland's good practice and experience. A total of 46 sampling locations were identified over the two phases in 2015 and 62 sampling locations were identified over the three phases of 2016, taking over 150 man-days of fieldwork. All possible springs, including those of the group water schemes, were identified through desk studies and walkover surveys. The sites were sampled using opaque glass bottles for grab sampling, and using activated charcoal and unbleached cotton wool detectors for background sampling. Samples were stored in darkened containers; bottle and charcoal samples were analysed in-house, by spectrofluorometer, cotton samples were analysed by visual inspection under UV light.

The road improvement project being undertaken in relation to the N5 National Route Study includes an investigation of the hydrogeology in the vicinity of the road. The project consultants, in consultation with Geological Survey Ireland, undertook dye tracing in the vicinity of the proposed road corridor. Details of these are also provided in Table 1.

Table 2: Dye input locations and conditions

Location	GSI Karst Database Feature No.	Date	Time	Weather	Flow	Dye input	Dye amount
Kilvoy	1727NWK001	25/05/2015	15:25	Dry,	flowing	Fluorescein	2.5 L
Carrowcreagh	1727NWK055	25/05/2015	14:55	Dry, overcast	trickle	Optical brightener	40 L
Ballyglass	1727NWK265	25/05/2015	16:30	Dry,	strong	Eosin	2 kg
Glenballythomas	1727NWK277	25/05/2015	16:15	Dry,	trickle	Rhodamine	10 L
Ballaghabawmore	1727SWK212	06/08/2015	16:00	Dry,	trickle	Fluorescein	3 L
Knockelgan east	1727SWK169	06/08/2015	15:30	Dry,	flowing	Rhodamine	10 L
Mullygollan	1727SWK005	06/08/2015	16:30	Dry, overcast	flowing	Optical brightener	50 L
Castleplunket main swallow	1727SWK213	12/08/2015	11:00	Dry, overcast	flowing	Fluorescein	3 L
Baloony/Tonroe	1727NWK270	12/08/2015	14:00	Dry,	flowing	Rhodamine	10 L
Carrowreagh/ Rathkineely	1727NWK188	15/06/2016	16:30	Dry,	flowing	Rhodamine	10 L
Carrowduff	1727NWK315	21/07/2016	16:30	Dry,	flowing	Rhodamine	10 L
Pollhesby	1729SWK045	14/10/2016	15:20	Dry,	flowing	Rhodamine	5 L
Pollcatron	1727NEK013	14/10/2016	16:05	Dry,	flowing	Fluorescein	1.2 L
**Polloweneen	1727NWK020	06/2015	-	-	-	Rhodamine	-
**Lugboy	n/a	12/05/2016	-	-	-	Fluorescein	-
**Polloweneen	1727NWK020	12/05/2016	-	-	-	Rhodamine	-

**** Traces carried for the N5 National Route Study**

RESULTS

Groundwater tracing results for the 2015 to 2016 period are summarised in Table 2, which shows the travel times for injected dyes to emerge at the springs, along with their calculated flow rates and topographical gradients from source to spring. Positive traces were proven to Corracreigh GWS, Mid Roscommon (Ogulla) GWS, Oran Ballintubber (Rathcarran) GWS, Peake Mantua GWS and Polecats GWS. Traces were also proven an unnamed springs just upgradient of Peak Mantua GWS spring and a spring just north of Rathcarran (Mid Roscommon GWS). As can be seen from Table 2, the trace from Carrowreagh/Rathkineely went to three locations: Peak Mantua, Corracreigh and to an unnamed spring south of Peak Mantua. Similarly the trace from Carrowduff near Oran Ballintubber GWS went to multiple locations: to both of the Rathcarran springs and to an unnamed spring approximately 1 km northwest of the Rathcarran Springs. The positive traces were rapid, appearing in the springs within days.

Table 3: Results of tracer tests 2015-2016

Input Site	GSI Karst Database Feature No	Output Site	GSI Karst Database Feature No	Input date	Flow Rate (m/hr)	Topographic Gradient (-)	Distance (km)	
Kilvoy swallow hole	1727NWK001	Not detected	n/a	25/05/2015	n/a	n/a	n/a	
Ballyglass swallow hole	1727NWK265	Not detected	n/a	25/05/2015	n/a	n/a	n/a	
Carrowcreagh swallow hole	1727NWK055	Corracreigh GWS spring	1727NEK017	25/05/2015	90 ± 13	0.011	6.9	
Glenballythomas swallow hole	1727NWK277	Corracreigh GWS spring	1727NEK017	25/05/2015	121 ± 27	0.012	6.2	
Ballaghabawmore swallow hole	1727SWK212	Spring	1727NWK108	06/08/2015	>192	0.013	4.3	
		Cargin Spring	1727NWK033	06/08/2015	>122	0.015	2.9	
Mullygollan swallow hole	1727SWK005	Mid Roscommon GWS Ogulla spring	1727NWK112	06/08/2015	>157	0.009	2.3	
Knockelgan east swallow hole	1727SWK169	Oran Ballintubber/ Rathcarran GWS spring 1	1727SWK210	06/08/2015	198 ± 77	0.008	5.7	
		Oran Ballintubber/ Rathcarran GWS Spring 2	1727SWK211	06/08/2015	205 ± 80	0.007	5.9	
Castleplunket main swallow hole	1727SWK213	Oran Ballintubber/ Rathcarran GWS spring 1	1727SWK210	12/08/2015	112 ± 27	0.004	6.6	
		Oran Ballintubber/ Rathcarran GWS spring 2	1727SWK211	12/08/2015	114 ± 27	0.003	6.7	
Baloony/Tonroe swallow hole	1727NWK270	Mid Roscommon/ Ogulla spring	1727NWK112	12/08/2015	107 ± 37	0.010	3.1	
Carrowreagh/Rathkineely swallow hole	1727NWK188	Peake-Mantua GWS source	n/a	15/06/2016	83 ± 28	0.017	2.3	
		Corracreigh GWS spring	1727NEK017	15/06/2016	95 ± 14	0.008	7.8	
		Spring	1727NWK207	15/06/2016	>56	0.021	1.2	
Carrowduff swallow hole	1727NWK315	Spring	n/a	21/07/2016	107 ± 23	0.004	5.8	
		Oran Ballintubber/ Rathcarran GWS spring 1	1727SWK211	21/07/2016	102 ± 22	0.005	5.5	
		Oran Ballintubber/ Rathcarran GWS Spring 2	1727SWK210	21/07/2016	101 ± 21	0.005	5.5	
Pollcatron swallow hole	1727NEK013	Pollacat Spring	1727NEK010	17/10/2016	42 ± 8	0.004	2.4	
Pollhesby swallow hole	1729SWK045	Pollacat Spring	1727NEK010	20/10/2016	67 ± 7	0.007	8.4	
Polloweneen swallow hole	1727NWK020	River downstream of Tobernacuilly spring	1727NWK014	Jun-15	n/a	n/a	4.6	**
Lugboy swallow hole	n/a	Drumullin Bridge	n/a	12/05/2016	n/a	n/a	3.9	**
Polloweneen swallow hole	1727NWK020	Pollacat Spring	1727NEK010	12/05/2016	>40 m/hr	0.004	10.6	**

**** Traces carried out for the N5 National Route Study**

ESTABLISHMENT OF ZONES OF CONTRIBUTION

The tracing programmes over 2015 and 2016, including those carried out for the N5 National Route Study, consisted of tracing from thirteen swallow holes. Eleven of these were proven to connect to one or more springs. The resultant data, along with the results from the pre-2015 tracing carried out by Hickey (2009) and Drew (2005), provides sufficient information on the overall groundwater flow directions to the main springs enabling zones of contribution to be delineated (Figure 3).

Peak Mantua GWS: The tracing carried out in 2015 did not prove any connection to Peak Mantua. The 2016 tracing carried out in Carrowreagh/Rathkineely yielded a connection to an unnamed spring upgradient of Peak Mantua, to Peak Mantua itself and to Corracreigh GWS. The southern portion of the ZOC overlaps with the catchment to Corracreigh. ZOC area = 6.4km^2.

Corracreigh GWS: The traces from Carrowcreagh and Glenballythomas (2015) indicate that the groundwater catchment extends westwards beyond the surface water/topographic catchment, illustrating that the groundwater flow directions in the Rathcroghan Uplands are not wholly related to topographic gradients and that surface river catchments cannot be delineated by topographical divides alone if they are to take into account groundwater inputs. The western boundary means that there is an overlap with the Peak Mantua ZOC as the trace from Carrowreagh/Rathkineely (2016) went to both GWS springs. ZOC area = 25.5km^2.

Oran Ballintubber (Rathcarran) GWS: The two traces, from Knockelgan East (2015) and Caarrowduff (2016), indicate that the groundwater catchment extends northwards of Rathcarran beyond the surface water/topographic catchments. The traces indicate a convergence on the Rathcarran springs. ZOC area = 44.5km^2.

Oran Ballintubber (Donamon) GWS: Updating the catchment to Rathcarran influences the previous zone of contribution delineated for Donamon (Meehan *et al*., 2015). However, there is still uncertainty regarding the boundary between Rathcarran and Donamon ZOCs in the vicinity of Carrowreagh, Rathnalulleagh and Peak townlands. ZOC area = 25km^2.

Mid-Roscommon GWS (Ogulla): The tracing carried out in 2015, from Mullgygollan, enabled the ZOC to be delineated. The tracing in 2016 did not result in any positives at Ogulla. The ZOC comprises the two northerly portions of the desk study based ZOC (Meehan, *et al.*, 2014). ZOC area = 17km^2.

Mid-Roscommon GWS (Carnalasson): No dyes were detected in surface water samples taken downstream of the spring at Carnalasson during the 2015 or 2016 tracing programmes. Within the currently delineated ZOC for this spring (Meehan *et al*., 2015), there are only a few mapped swallow holes and none were deemed suitable for dye input. Future tracing programmes should take this into account, especially considering that a previous tracer test at Carnalasson showed a questionable ‘weak’ positive trace from a swallow hole located 6 km west of the spring (Drew, 2005). ZOC area = 17km^2.

Polecats GWS: Tracing from Pollhesby swallow hole (2016) shows that the ZOC extends northwest. The tracing from Polloweneen (N5 Study, 2016) and Pollcatron (2016) swallow holes indicate that the ZOC extends southwest onto the Rathcroghan Uplands toward the N5 and the Peak Mantua and Corracreigh GWSs. The trace from the swallow hole in Lugboy (N5 Study, 2016) provides evidence for the south-eastern boundary of the ZOC. Note that the 2015 trace at Kilvoy, carried out by the Geological Survey, did not appear to go to any of the sampled sites. In this case Polecats GWS was not sampled as it was considered not likely to be connected, owing to the several significant water courses between Kilvoy and Polecats GWS. However, the Kilvoy swallow hole is just south of Polloweneen swallow hole, which was a proven connection to Polecats GWS. It is now assumed that the Kilvoy swallow hole is connected to Polecats GWSs. ZOC area = 52km^2.

Rockfield Springs (former Public Water Supply): The tracing by Drew (2005) in the Rockfield Spring area, show groundwater flow directions contrary to surface water flow, indicating complicated interactions between surface water and groundwater. The springs were not sampled during the 2015 or 2016 tracing programmes and the original ZOCs have not been amended. ZOC area = 17.5km^2

Castlerea PWS: The zones were delineated by Lee and Kelly in 2003, as part of an intensive field based study. The springs were not sampled during the 2015 or 2016 tracing programmes; therefore there are no amendments to the original ZOC. ZOC area = 11.7km^2.

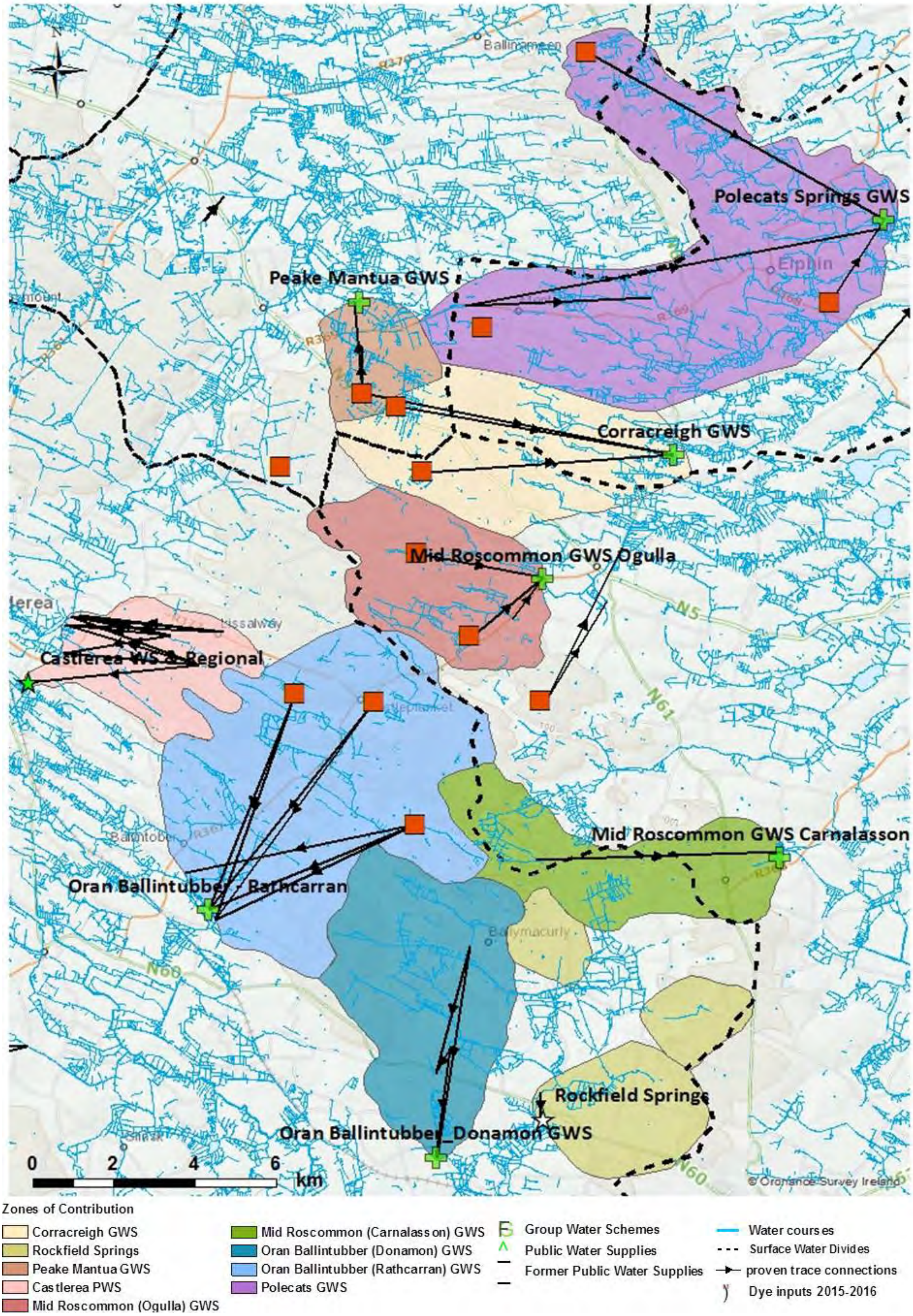

Figure 4 Zones of Contribution delineated for the Water Schemes

IMPLICATIONS FOR THE RATHCROGHAN UPLANDS AND LOOKING TO THE FUTURE

The established ZOCs are now much more robust, but there are inherent uncertainties in the boundaries of the ZOCs. Further tracing would be useful in the northern and southern portions of the study area. It would be beneficial to do additional tracing in the Corracreigh, Mid Roscommon (Carnalasson) and Polecats ZOCs to improve the information on the groundwater flow patterns and boundaries. Water balance calculations are used to support the hydrogeological mapping and to confirm that the ZOC delineated is sufficient to supply the source. All of the ZOCs are larger than those required to meet their respective abstractions; however, the areas relate to the total spring discharge and the important unknown is the mean flow from the springs (abstraction plus overflow). This may need to include other large springs that occur in close proximity to the abstraction springs, as well as the springs that occur in the low-lying perimeter of the Rathcroghan Uplands.

The results of the study were discussed with representatives from the Group Water Schemes and the National Federation of Group Water Schemes. The reaction was positive; however, there was some surprise at the how extensive some of the Zones of Contributions are and the implications for land-use planning and groundwater protection. The general consensus was that there needs to be a heightened awareness by the public of (a) the role of the group water schemes in providing sufficient and clean drinking water, and (b) groundwater protection, especially in relation to agricultural practices and waste water management. It is expected that public dissemination of the results of the tracing programme will occur in the near future, through newspaper articles followed by public meeting(s).

The dye tracing programme feeds into two additional projects being carried out by the Geological Survey Ireland groundwater section.

1. Data from the tracing programme has been used to populate the karst and tracer databases, which can be accessed through the GSI online Groundwater Data Viewer (http://spatial.dcenr.gov.ie/GeologicalSurvey/Groundwater/index.html)
2. Results and insights from the tracing programme are being used by the recently established GWFlood project which aims to develop a monitoring programme and advisory service in relation to groundwater flooding.

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POSTER ABSTRACTS

AGRO-CHEMICALS IN IRISH KARST AND FRACTURED BEDROCK AQUIFERS: A PILOT STUDY OF ANTHELMINTIC DRUG RESIDUE OCCURRENCE

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ABSTRACT

Emerging Organic Contaminants (EOCs) are chemicals that have not been included in national or international monitoring programmes or in existing environmental quality regulations, but are being introduced into the environment by anthropogenic activities. In Ireland, due to increased intensification of the food production system, agro-chemicals such as veterinary drugs have become a critical component in animal husbandry. Given such high demands on the performance of Irish agriculture, in addition to the imminent pressures attributed to the fast approaching Harvest 2020 and more recent FoodWise 2025, the usage of veterinary drugs is set to continue. This has led to these agro-chemicals being considered as primary emerging contaminants of concern. The administration and application of such substances can potentially lead to their occurrence in groundwater. As a result, loss of veterinary drugs to underground water is not only a matter of international scientific interest, but potentially a health risk to humans and the environment.

This work presents the preliminary findings of a pilot study on the occurrence of anthelmintic residues in Irish karst and fractured aquifers. Anthelmintics, a class of anti-parasitic drug, are one of three groups of agro-chemicals being investigated as part of this overall iCRAG (Irish Centre for Research in Applied Geosciences) project. A multi-residue Solid Phase Extraction Ultra High Performance Liquid Chromatography Tandem Mass Spectrometry (SPE-UHPLC-MS/MS) method was developed and applied in a pilot study for the determination of 36 anthelmintic drugs in water samples from high risk sites targeted in terms of source and pathway factors. Sites were selected based on (a) intensity of agricultural activity and/ or (b) groundwater vulnerability, within the zones of contribution. Up to five different anthelmintic residues were detected in four of fifty-two groundwater samples (8%) and four of twenty surface waters (20%) analysed. Detections were of the order of 1-31 ng L^{-1}. Sites with groundwater detections had zones of contribution including areas of high and extreme groundwater vulnerability, associated with shallow Quaternary deposits or karst conduit flow. Detections were recorded for just one site with karst conduit flow, with non-detections for the vast majority of vulnerable karst sites in the west and south-east of Ireland. Work is currently being undertaken to investigate whether the absence of detections at these other apparently high risk sites may be due to the timing of sampling in relation to groundwater recharge events.

The work carried out as part of this overall project will help to assess whether or not anti-parasitic drugs are an issue in Irish groundwater. In addition this work will contribute to evaluating environmental effects of Food Harvest 2020 and Food Wise 2025 in terms of investigating such potential rural groundwater concerns, which may not previously have been considered adequately in an Irish context. The comprehensive analytical methods developed for this project will also contribute to broadening the knowledge and understanding of occurrence and fate (mobility and behaviour) of both parent and transformation products of these contaminants in the environment.

This publication/presentation has emanated from research supported in part by a research grant from Science Foundation of Ireland (SFI) under Grant Number 13/RC/2092 and is co-funded under the European Regional Development Fund and by iCRAG industry partners. The first author gratefully acknowledges funding from the Teagasc Walsh Fellowship Scheme.

Keywords: agro-chemical, veterinary drugs, anthelmintics, groundwater, karst

SOURCING ARSENIC IN GROUNDWATERS OF THE LONGFORD-DOWN TERRANE OF NORTH-EAST IRELAND

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ABSTRACT

Arsenic (As) contamination of groundwater drinking resources affects up to 200 million people worldwide, in over 100 countries. Arsenic is known to be a powerful carcinogen, and due to its odourless and tasteless qualities in water it may be consumed for prolonged periods of time, leading to chronic arsenic poisoning. Geological environments similar to those in which high levels of dissolved As occur elsewhere are common in Ireland, (e.g. sulphide bearing volcano-sedimentary sequences and unconsolidated glacial, fluvioglacial and alluvial deposits), yet reliable ppb-level As data for groundwater are relatively sparse. Recent investigations have indeed shown arsenic to be an emerging element of concern in Irish groundwaters, exceeding both the global recommended limit of 10 µg L^{-1} set out by the World Health Organisation (WHO), and also the Irish groundwater threshold value (GTV) of 7.5 µg L^{-1}.

The primary sources of arsenic in the environment are natural but the mineralogical sources and remobilisation processes which lead to its accumulation in some groundwaters are not yet fully understood. The work presented here focuses on an area of known elevated groundwater As within a fractured-bedrock aquifer in the Longford-Down Terrane of NE Ireland. Arsenic occurs in groundwater at elevated levels (up to 60 ppb) at basalt dyke contacts within both the Palaeogene Slieve Gullion Complex and Silurian-Ordovician greywacke-shale units. The contamination occurs in privately-owned wells, which remain unregulated in Ireland.

Three drill cores were retrieved in the area by the Geological Survey of Ireland during late 2015 and were subsequently logged. Bulk geochemical data (ICP-MS & ICP-AES), alongside preliminary Scanning Electron Microscopy work, coupled with energy dispersive X-ray spectroscopy are discussed. Data for sulphide minerals and secondary iron oxy-hydroxides that occur along shallow angle fractures are presented to identify potential mineralogical source(s) for the arsenic.

A total average As content of c. 3 ppm for all bulk-rock samples is similar to estimated upper crustal abundances of 2–5 ppm. Several samples of greywacke and basalt are however more elevated, ranging between 10–17 ppm. Within these lithologies a range of disseminated sulphide minerals have been identified including arsenic-bearing sulphides, which are also associated with cobalt (Co) and nickel (Ni). Sulphides are also present within quartz-calcite veins, however, no arsenic has been found to be associated with these. Mass balance calculations indicate that relatively large volumes (c. 4000 grains/g) of small (1500 µm^3) disseminated sulphides would be required to account for the observed whole-rock concentrations in the 10-17ppm range.

SESSION V

REACTIVATION OF KARST SPRINGS AFTER REGIONAL MINE DEWATERING IN THE TATA AREA, HUNGARY

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ABSTRACT

Mine dewatering operations in the Transdanubian Mountains, Hungary between 1960 and 1990 resulted in the vanishing of major karst springs. Following the termination of mining operations, the former springs started to reactivate. Reappearing springs cause significant environmental problems in Tata and other localities. The aim of this study was to characterise the recovering flow system, to delineate affected areas and to provide predictions of spring reactivation.

Spring locations in Tata are aligned with deep tectonic structures both in uncovered and confined karst areas. The analysis of well hydrographs indicates that there is no hydraulic connection between shallow and carbonate aquifers. The prediction of karst water levels suggests that equilibrium will be reached by 2018 at approximately 140 m ASL.

The chemical composition of most reactivating springs indicates a dolomitic aquifer origin. Some springs discharge shallow groundwater and show signs of local pollution.

Geochemical data indicates significant changes in karst water chemistry in response to mine dewatering and the following recovery. While bicarbonate concentration decreased, sulphate concentration increased during mine dewatering operations. Recent hydrochemical data indicates that the concentration of main water components started to rebound towards their original values around the mid-2000's, presumably indicating the geochemical recovery of the groundwater system. The available data suggests a delay of 10-20 years between the changes in extraction rates and the subsequent hydrochemical changes. Chloride as a conservative anion was used to study mixing processes. The isotopic composition of karst waters shows Pleistocene recharge. Based on isotopic data it can be assumed that the karst waters in the Tata region are older than 10,000 years. No signs of recent infiltration could be detected in the karst water.

INTRODUCTION

The study area is located on the northern edge of the Transdanubian Mountains, Hungary (Figure 1.). The Tata springs represent the natural outlet of the Transdanubian karst aquifer. The aquifer is hosted in Triassic limestones and dolomites. The Transdanubian karst system was strongly affected by mine dewatering related to bauxite and coal mining from the beginning of the 1950's (Figure 2.). The intense karst water abstraction caused regional groundwater depressurisation (VITUKI, 2000; Csepregi, 2007), and as a consequence, several springs in the Tata area disappeared during this period. Following the termination of mining operations in the area, the flow system started to recover. Since the late 90's the karst water table has risen by more than 40 metres in the Tata area. As a result, some of the former springs reactivated and further springs are expected to reappear.

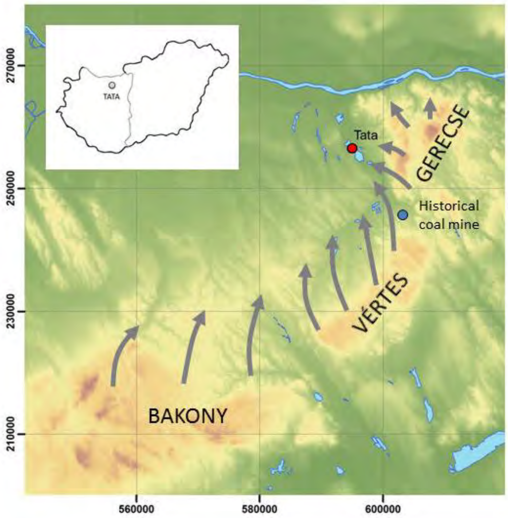

Figure 1. Site location with dominant groundwater flow directions in natural state.

During the 1970's significant developments took place in areas previously used as agricultural land. Currently 30% of the population lives in this area. The reactivating springs cause significant environmental problems both from the geotechnical, sewerage and water quality points of view.
The aim of our study was to understand the hydraulic and hydrogeochemical behaviour of the recovering flow system, to delineate affected areas and to provide predictions on the location and timing of spring reactivation.

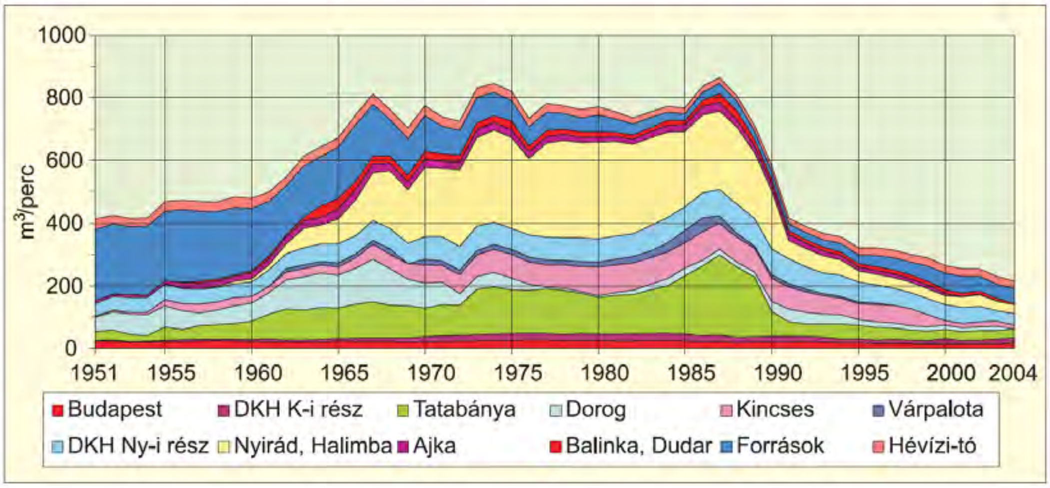

Figure 2. Total groundwater extracted by mining operations in the Transdanubian Mountains. (After Csepregi, 2007).

HYDROGEOLOGICAL CONDITIONS

The karst springs at Tata represent one of the main natural outlets of the Transdanubian carbonate aquifer system. The regional erosion base of the region is the Által-ér creek. The recharge areas of the springs are located in the North-Western uncovered carbonate aquifers of the Gerecse and Vértes Mountains, and in the North-Eastern karst areas of the Bakony Mountains (Csepregi, 2002) (Figure 1.).

The karst springs in the Tata area are located along a chessboard-like fault system (Figure 3.). Before the beginning of mine dewatering operations, there were several active springs in the area, at topographic elevations between 118-141 m ASL with yields between 1- 81,000 litres/minute (Horusitzky, 1923). Spring locations are aligned with deep tectonic structures both in uncovered and confined karst areas. Although there is little evidence on karstification, this indicates that concentrated groundwater flow takes place along tectonic structures representing preferential flowpaths. The confining marls in the city of Tata do not block groundwater discharge to the surface along tectonic features.

Potentiometric data in the monitoring wells indicate a very flat karst water surface. The hydraulic gradient is in the range of 0.001-0.0005 (m/m). The natural regional flow direction in the carbonate basement was from South-West to North-East. As a consequence of mine depressurisation, the natural flow directions were altered because of a large depression cone located South-East of the Tata area. The karst water level in the vicinity of Tata was around 136 m ASL based on data from January 2014.

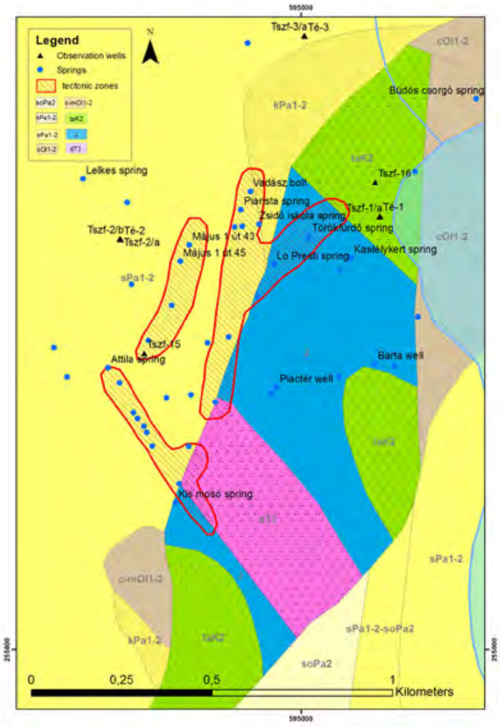

Figure 3. Geological settings and locations of springs and monitoring bores. Pa and Ol indicate confining Pannonian and Oligocene sediments. T, J and K indicate the unconfined zones of the Triassic, Jurassic and Cretaceous carbonate aquifer.

The original, undisturbed karstic water level data differs between various references. We assume in our study that the karstic level was about 140 m ASL near Tata based on historical spring levels and we expect a similar water level by the end of water level recovery, knowing that this also depends on water extractions and on future climate conditions.

The Mesozoic karst aquifer is overlain by a series of younger sediments which contain shallow groundwater bodies. The main shallow aquifer is unconfined and is a few meters thick. The groundwater table follows the ground surface at an average of 1-3 meters depth and plunge to larger depths in the hilly areas. The flow direction of the shallow groundwater is generally in the direction of the Által-ér creek. There is no hydraulic connection between shallow and karst aquifers.

PIEZOMETRIC MONITORING DATA

The changes in groundwater levels in the monitoring wells between 2001 and 2014 are shown in figure 4. Wells Té-1, Té-2 and Té-3 are screened in the main karst aquifer. Wells Tszf-1 to Tszf-18 are screened in the shallow aquifer.

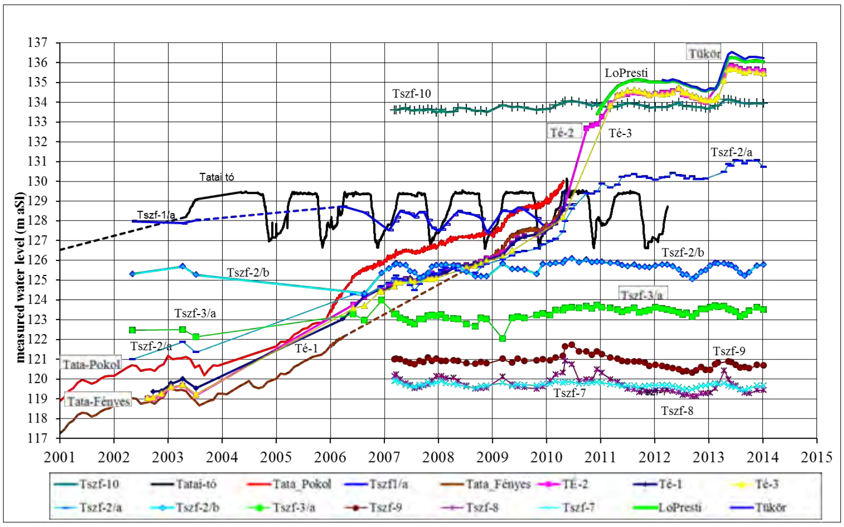

Figure 4. Time series of monitoring wells at Tata.

WATER LEVEL PREDICTION

One of the practical goals of the study was to predict when the flow system reaches natural equilibrium. The karst water level prediction was based on time series of several karst water monitoring wells. A logarithmic trend line was fitted on the time series of wells Té-1, Té-2 and Té-3. The application of a logarithmic function for curve fitting was based on the assumption that the recovery follows the Cooper and Jacob (1946) well function. The Cooper and Jacob solution is an approximation of the Theis (1935) non-equilibrium method.

Curve fitting was performed for the 2001-2009 period (Figure 5), since the extremely high precipitation in 2010 broke the trend of previous years, causing a more than 4 meters rise in karst water levels.

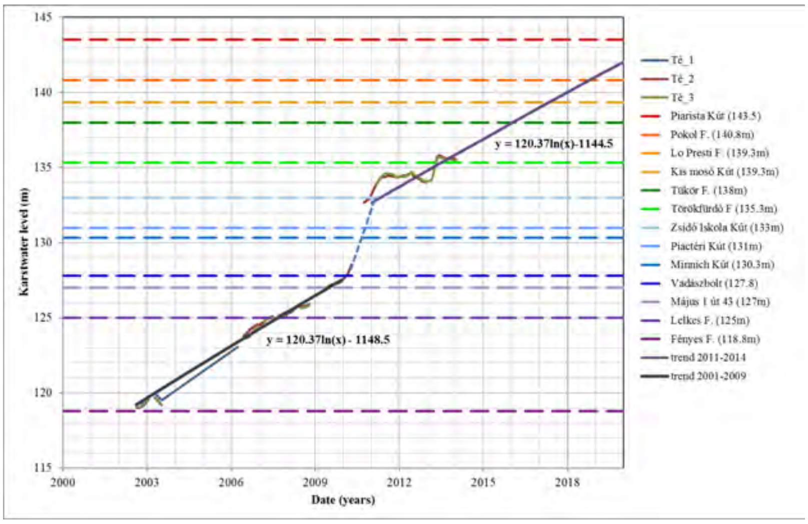

Figure 5. Karst water level prognosis based on time series of the karst water monitoring wells in the Tata region and the topographic levels of main springs.

The trendline was shifted by 4 metres in 2010 to represent the trend characteristic of the following years. The prediction based on curve fitting suggests that equilibrium karst water level will be reached around 2018 at approximately 140 m ASL. This prediction is based on the assumption that water abstraction rates and climatic conditions recorded between 2000 and 2009 remain constant during the following years. Any significant change in these parameters might influence the recovery process and thus the time of spring reactivation.

GENERAL HYDROGEOCHEMICAL CHARACTERISTICS

The karst waters in the Tata region are CaMgHCO3 type, indicting they come from a dolomitic aquifer. Piper diagram (Figure 6) shows the data of karst water wells (Tata 26, 27/A, 28, 34, 41 and Karst ‘recent’ representing Tata 28 and Tata 34 data of samples collected in 2014), springs (Fényes, Lo Presti, Pokol, Törökfürdő, Kastélykert, Büdös csorgó, Zsidó iskola), seepages (43 Május 1 street, 45 Május 1 street, Attila, Lelkes, Vadászbolt), a stream (Kismosó) and a dug well (Kismosó well) next to the stream.

The chemical composition of deep wells, the Fényes, Lo Presti, Törökfürdő, Pokol springs and the new Attila seepage and seepages at Május 1.u 43 and 45 clearly show karst water composition with $CaMgHCO_3$ or $MgCaHCO_3$ water types.

The chemical composition of Kastélykert spring and of the dug well at Kismosó stream are similar, both having a $CaMgHCO_3SO_4$ water type. This shows the effect of mixing with shallow groundwater and potentially local pollution. The high nitrate concentration in the Kastélykert spring also supports pollution from an anthropogenic source.

Sampling sites Büdös csorgó and Lelkes seepage have a distinct chemical composition with $MgCaSO_4HCO_3$-$MgCaNaSO_4HCO_3$ water type.

Kismosó stream as a local discharge area does not show any connection with the karst water, has a $CaMgSO_4$ water type, and is highly polluted (not discussed in this paper).

The chemistry of shallow groundwater (TSZF) wells is typically of $CaMgHCO_3SO_4$ type, but reflects the effect of the local near surface geology and hydrogeology. While the karst waters of the region show a uniform composition, the shallow groundwater shows a variable composition. Many of the shallow groundwater wells are locally polluted with nitrate.

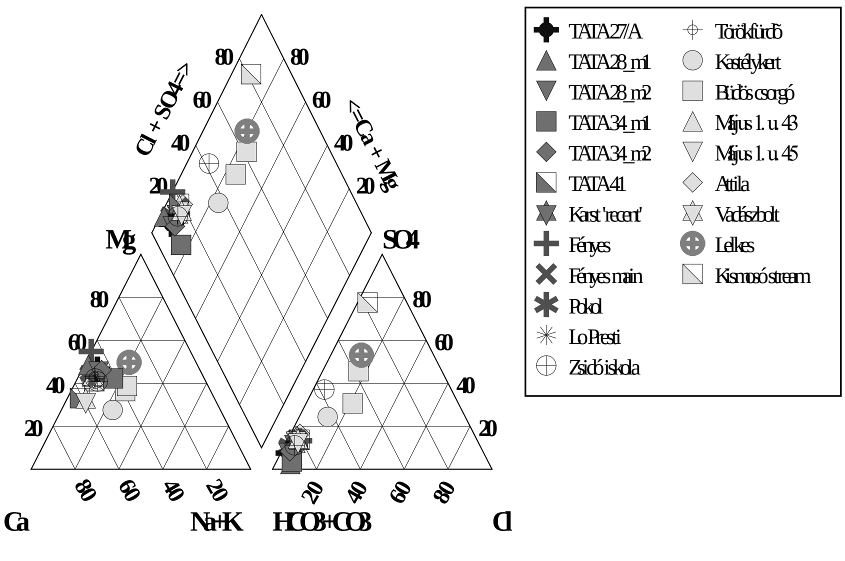

Figure 6. Chemical characteristics of groundwater based on data of karst water wells, springs, seepages, a stream and a dug well.

EFFECTS OF MINE DEWATERING ON GROUNDWATER CHEMISTRY

The effect of mining activities on the karst water composition is shown in Figure 7a where the hydrogen-bicarbonate data of some representative karst wells and springs are plotted against time. It can be seen that the hydrogen-bicarbonate content dropped at the beginning of 1983, with median values decreasing from 476 mg/l to 458 mg/l. This might indicate a hydrochemical response to aquifer dewatering having started in the early 50's and intensified around 1972-73 in the Tatabánya region.

Samples collected from Lo Presti karst spring and the two drinking water supplying wells (Tata 28, Tata 34) in the last quarter of 2014 and in 2015 show slightly increasing concentrations (median 3 = 468 mg/l). These concentration changes suggest a recent change in karst water composition starting probably from the mid-2000's.

The decrease in the hydrogen-bicarbonate content was accompanied by an increase in sulphate content from 1977 (Figure 7b), which supports changes in groundwater chemistry in response to mine dewatering. The initial 10 mg/l sulphate median values rose to 59-67 mg/l by 1986-1987. The data of the last few years show a stable or even slightly lower sulphate value (median 3 = 54 mg/l) which might be a sign of the beginning hydrochemical regeneration of the karst water flow system.

No data was available on anion concentrations before 1967. From the beginning of the available data series chloride concentrations remained stable until about the mid-2000's. Recent data show a clear decrease in chloride concentrations (Figure 7c). This may indicate a hydrochemical response to the recovery of the karst water flow system.

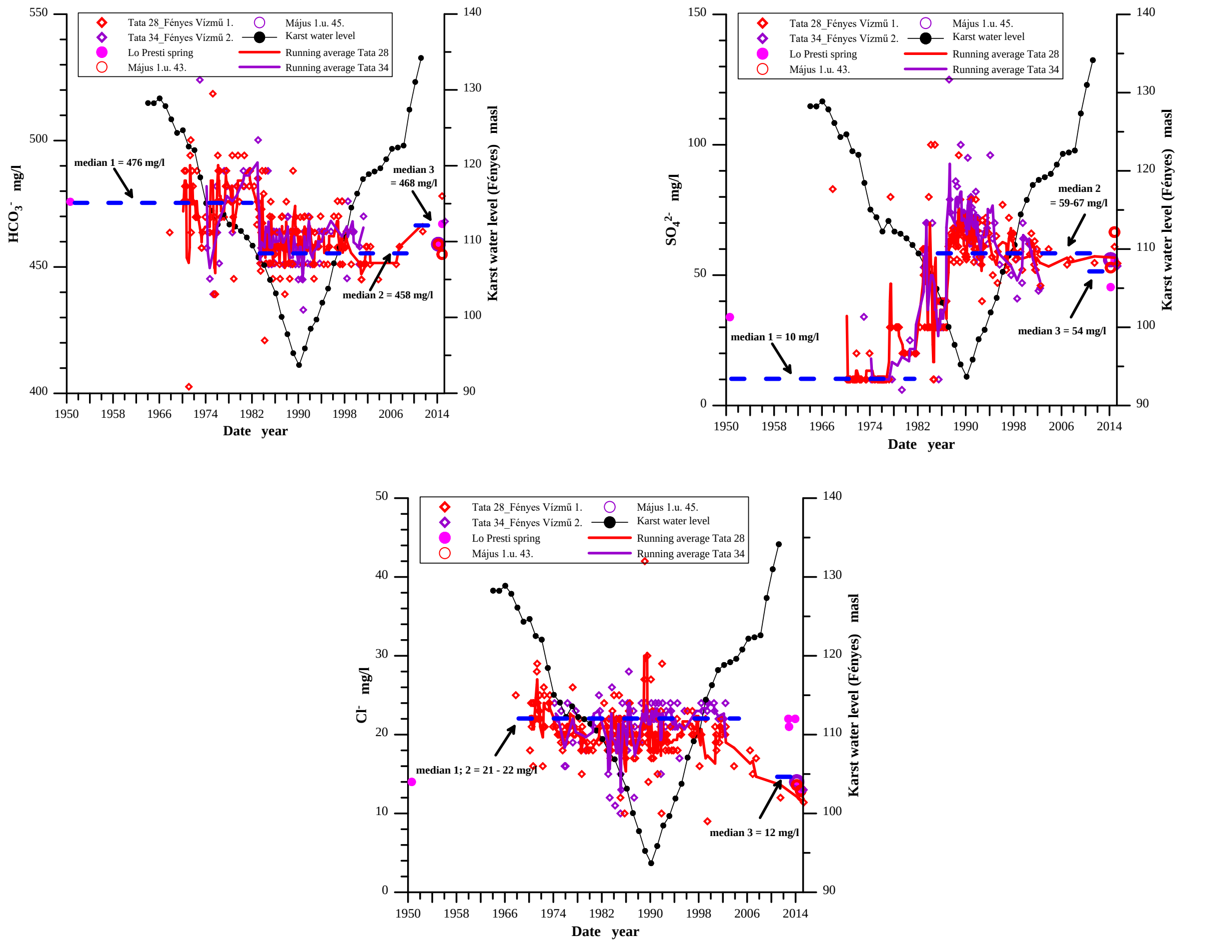

Figure 7. Changes with time in the hydrogen-bicarbonate (a), sulphate (b) and chloride (c) concentrations based on some representative karst water wells, spring and seepages.

Groundwater depressurisation started in the early 1950's with increasing abstraction rates throughout the following years. The maximum amount of abstracted karst water reached its peak in 1988 with 240 m^3/min, after an almost 25 years long period with a similarly high abstraction level. In the following years, mostly between 1989 and 1992, with the progressive mine closures the karst water abstraction rates dropped to about 30-40 m^3/min (Figure 2). As Figure 7 shows the deepest point in karst water level was reached in 1990.

The remarkable changes in the concentration of hydrogen-bicarbonate around 1983-84 and of sulphate between 1977 and 1986-1987 are assumed to indicate the hydrochemical response of the groundwater system given to large-scale aquifer dewatering.

Recent hydrochemical data indicates that the concentration of main water components started to rebound towards their original values around the mid-2000's, emphasised from 2010, presumably indicating the hydrochemical recovery of the groundwater system. The comparison between abstraction rates and chemical data suggests a delay of 10-20 years between groundwater chemistry and groundwater flow conditions.

Although further studies are required to support this conclusion, it can be assumed that the hydrochemical changes were caused by the reversal of hydraulic gradients and the subsequent changes in regional flow directions between the natural north-easterly flow and a depressurised south–westerly groundwater flow.

ISOTOPE GEOCHEMICAL CHARACTERISTICS

Some of the samples were analyses for δD-$\delta^{18}O$, $\delta^{13}C$, ^3H and ^{14}C in order to get a better understanding of the karst water system, and the origin, as well as the relative or absolute ages of water from the springs and seepages.

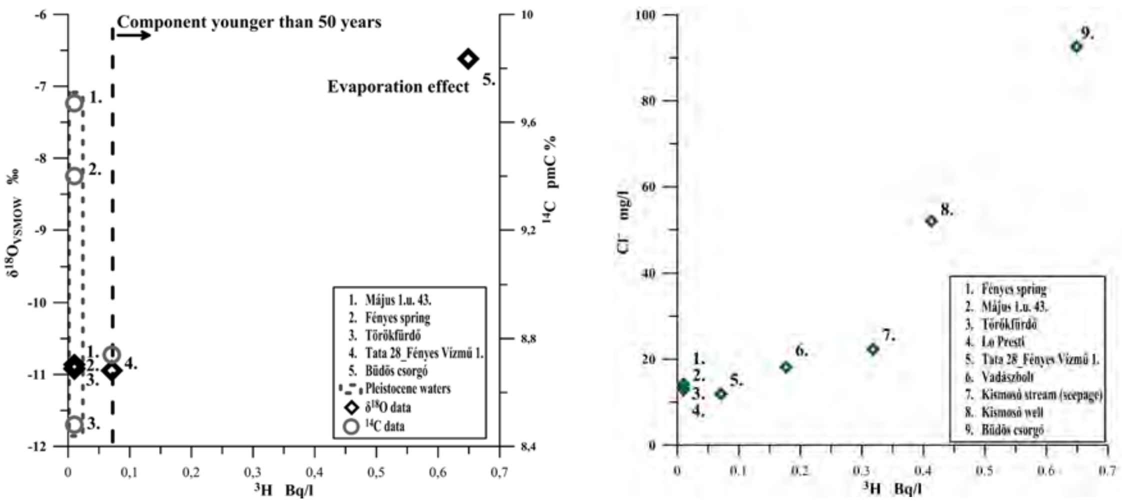

Figure 8. Isotope data characteristics.

It can be clearly seen that the tritium content of the sampled karst waters is below the detection limit (0.059 Bq/l), which means there is no precipitation component younger than 50 years in the karst waters (Figure 8a). This also means that shallow groundwater does not mix with karst waters at the surveyed sites.

The isotope compositions of the sampled karst waters clearly show Pleistocene recharge except for well K-28. Based on this it can be assumed that the karst waters in the Tata region are older than

10000 years. Importantly, despite a rise in the karst water no sign of recent (young) infiltration could be detected in the karst water. The dug well at the Kismosó stream has a significant or wholly recent infiltration origin. Based on the tritium data, mixing with karst water cannot be completely excluded, but neither the main nor the trace element data support the possibility of mixing. Its high chloride concentration shows mixing with shallow groundwater. More information on mixing could be gained by using δD- $\delta^{18}O$ data. Figure 8b shows that with an increase of the recent infiltration component, shown by an increase in the tritium content, there is a significant increase in the chloride concentration which supports a mixing with shallow groundwater at these sites.

CONCLUSIONS

Spring locations at Tata are aligned with deep tectonic structures indicating that concentrated groundwater flow takes place along tectonic structures.

The prediction of karst water levels based on physical curve fitting suggests that equilibrium karst water level will be reached around 2018 at approximately 140 m ASL.

The karst waters in the Tata region are $CaMgHCO_3$ type, indicating that they come from a dolomitic aquifer. The shallow groundwater shows a variable composition.

Geochemical data indicates significant changes in karst water chemistry in response to groundwater depressurisation and the following recovery. While bicarbonate concentration decreased, sulphate concentrations increased during mine dewatering operations. Recent hydrochemical data indicates that the concentration of main water components started to rebound towards their original values around the mid-2000's. This presumably indicates the geochemical recovery of the groundwater system. The available data suggests a delay of approximately 10-20 years between the changes in extraction rates and the subsequent hydrochemical reactions. Karst waters of Tata are older than 10,000 years. Despite rising water levels, no signs of recent infiltration could be detected in karst water.

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SESSION VI

MONITORING, MAPPING AND MODELLING GROUNDWATER FLOODS IN IRELAND

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ABSTRACT

The phenomenon of groundwater flooding poses a significant flood hazard to many rural communities in the lowland karst limestone regions of Ireland. The unprecedented flood events of recent years have highlighted the need for a greater understanding of groundwater flooding as a geohazard, and to improve our ability to quantify the location and likelihood of flood occurrence. In order to address this knowledge gap the Geological Survey (part of the new Department of Communications, Climate Action and Environment) has commenced a collaborative project with the University of Dublin Trinity College to investigate flooding specifically related to groundwater and turloughs. Through the monitoring, mapping and modelling of groundwater floods this project will provide essential technical knowledge to relevant stakeholders and decision makers, enabling them to make scientifically-informed decisions regarding groundwater flood mitigation and prevention.

INTRODUCTION

The winter of 2015/2016 saw unprecedented levels of rainfall across the Republic of Ireland. Over 600mm of rainfall fell across the island of Ireland between December and February, representing 190% of the long-term average and making it the wettest winter on record in a rainfall time series stretching back to 1850 (McCarthy et al., 2016; Noone et al., 2015). The sustained heavy rainfall caused exceptional and widespread flooding, with rivers across the country bursting their banks and registering some of the highest levels on record. Winter 2015/2016 also saw the most extensive groundwater flooding ever recorded on the karstic limestone plains in the west of Ireland. The protracted nature of groundwater flooding, lasting for many months in some cases, caused prolonged hardship to rural communities where they struggled to prevent the inundation of homes and workplaces amid unparalleled disruption to transport networks. Sustained flooding of agricultural land also posed serious welfare risks to livestock and impacted heavily on agriculture.

Groundwater flooding events in Ireland are centred on the limestone areas of the western lowlands, which extend from the River Fergus in Co. Clare in the south upwards to the areas east of Lough Mask and Corrib in Co. Galway and southern Co. Mayo. The prevalence of groundwater flooding in the western counties is fundamentally linked to bedrock geology. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between ground and surface waters, which leaves them susceptible to groundwater flooding (Naughton et al., 2015). During intense or prolonged rainfall, the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly reaches capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Mott Mc

Donald, 2010; Naughton et al., 2012). The main examples of groundwater flooding in Ireland are turloughs, temporary lakes which ordinarily flood on an annual basis due to winter rainfall and groundwater levels. There are over 400 recorded examples of turloughs across the country, with the majority located in the limestone lowlands in counties Roscommon, Galway, Mayo and Clare. Due to the record breaking rainfall in the winters of 2009 and 2015, turlough flooding impacted on dozens of homes, as well as causing widespread and extended disruption to transport networks across the region (figure 1).

Fig. 1: Flooding in the Gort Lowlands, Co. Galway, during the winter of 2015/2016

Groundwater flood risk management poses its own set of technical, environmental and socio-economic problems that differentiate it from other flood forms (e.g. fluvial, coastal etc.). Groundwater flooding can occur in a discontinuous manner across the landscape, often with no indication of flood risk prior to an extreme event. Unlike river flooding, where the flood is typically linked to high intensity rainfall, groundwater flooding is driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration. Furthermore, the long-term hydrometric data required for traditional flood frequency analysis does not exist for groundwater flooding, impeding the calculation of flood risk (combination of likelihood of an event and the damage caused by the event) as required in flood defence scheme assessments.

GEOLOGICAL SURVEY IRELAND GROUNDWATER FLOOD PROJECT

Recent flood events have reinforced the need for a greater understanding of groundwater flooding as a geohazard, and improve our ability to quantify the location and likelihood of flood occurrence. In response to the serious flooding of winter 2015 specifically related to turloughs, the Programme for a Partnership Government (2016), under the area of Climate Change and Flooding, contains the following objective: *"Turlough Systems: We will provide resources to the OPW to commission studies into individual problematic (prone to flooding) Turlough systems, if requested by a local authority or another relevant State agency"*. Geological Survey Ireland (GSI), a division of the Department of Communications, Climate Action and Environment (DCCAE), were in a position to help deliver on this commitment through the existing groundwater and karst expertise and by the development of a new three-year project on Groundwater & Turlough Monitoring and Modelling. A detailed project plan was developed over summer 2016 and approved by DCCAE as an additional project of the GSI Groundwater Programme and funding was allocated in Budget 2017.

Through the groundwater flood project (GWFlood) the Geological Survey, in collaboration with the University of Dublin Trinity College, is working with local authorities and government agencies to address the knowledge gap regarding these complex karst systems and provide the necessary information and tools to make scientifically-informed decisions with regards to groundwater flood risk management. The proposed study aims to provide the requisite data to address this knowledge gap by establishing a permanent monitoring network, as well as developing analytical tools to help address issues surrounding groundwater flood mapping, frequency estimation and likely climate change impacts. The main objectives of the project are to:

- Establish a permanent monitoring network to provide long-term quantitative groundwater flooding data
- Develop groundwater flood hazard maps and real-time monitoring of groundwater flooding
- Develop modelling/analysis methodologies for estimating groundwater flood frequency and the assessment of potential flood mitigation strategies for designated areas
- Analyse the potential impact of climate change on groundwater flooding
- Improving general understanding of karst hydrodynamics through targeted studies using multidisciplinary investigation techniques
- Investigate the influence of structural controls on turlough hydrogeology using 3D geological modelling and visualisation techniques
- Communicate and disseminate project outputs to key stakeholders

The main project work and deliverables can be summarised under the headings of flood monitoring, mapping and modelling and are further described below.

FLOOD MONITORING

Hydrometric data is a crucial component to understanding the dynamics of surface and groundwater flow systems. Information such as stage and discharge are recorded at gauging stations across the country in rivers, lakes, boreholes and coastlines, providing data vital to local authorities and planning agencies for effective flood risk management. However, consistent long-term hydrometric data do not exist for groundwater flooding applications. A primary objective of this project is thus to establish a monitoring network to provide key baseline data for flood risk and habitat management applications. While some turlough systems posing a flood risk, such as the Gort Lowlands, are relatively well understood there is limited hydrogeological knowledge on most Irish karst groundwater flow systems. The project commenced in October 2016 and to date, over 40 exploratory monitoring stations have been installed in counties Galway, Clare, Roscommon and Longford (figure 2). Data from these sites will help develop preliminary understanding of the hydrodynamics and flooding potential of turlough systems across key catchments, and inform the site selection process for the permanent monitoring network. A subset of 20 sites representative of the spectrum of groundwater flooding conditions in Ireland will be established as permanent telemetered stations providing real-time information on groundwater flood conditions. The installation of permanent monitoring stations which will commence in summer 2017 will continue throughout the summers of 2018 and 2019.

Fig. 2: Installing water level monitoring in Ballinturly turlough, Co. Roscommon (inset: logger housing)

FLOOD MAPPING

The ability to describe and map how floods develop and recede accurately and at a large spatial scale is a prerequisite for effective flood risk management. This poses significant problems for monitoring groundwater flooding, however, as floods tend to occur in isolated basins across the landscape and so would require an impractical amount of field monitoring to provide a complete picture. Remote sensing (RS) and Geographical Information System (GIS) approaches offer significant advantages in this respect. Passive satellite imagery, such as the USGS Landsat or ESA Sentinel programmes, can be used to image and delineate floods at a catchment scale (figure 3). In the case of Landsat, a long historical archive of images also allows us to look at past flood conditions and provides some data with which to validate hydrological models. However, an obvious limitation of satellite systems which require a clear view of the earth's surface is the issue of cloud cover. When cloud cover is extensive, as is often the case during winter floods, no useful data can be collected. Under these conditions active systems, such as synthetic aperture radar (SAR), are extremely useful as they are not impacted by cloud cover. An additional benefit of SAR is the frequency of image capture; the ESA Sentinel 1 satellite collect SAR images over Ireland at every three to six days going back to 2014 and so provide high temporal resolution with which to map groundwater flood events.

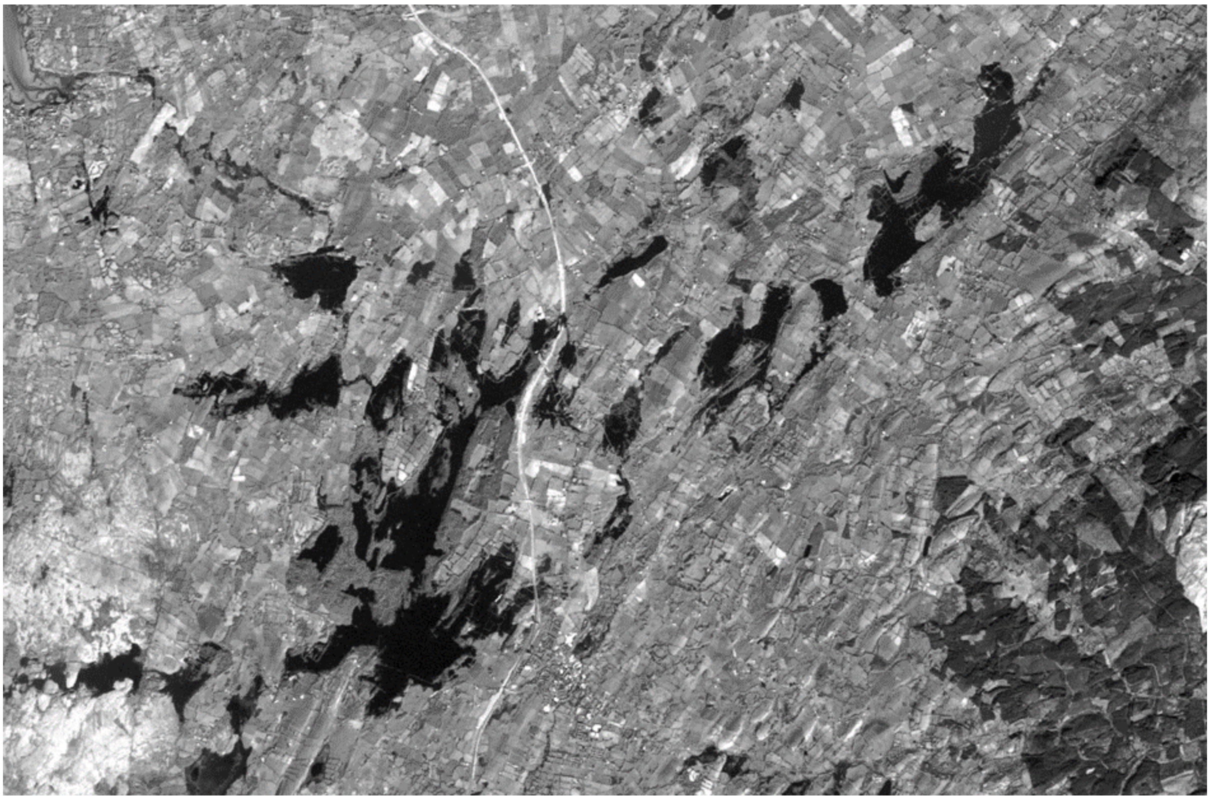

Fig. 3: Landsat 8 image showing flooding in the Gort Lowlands, February 2016

Numerous studies have demonstrated the efficacy of delineating water bodies using remotely-sensed data (Amitrano et al., 2014; Feyisa et al., 2014; Martinis et al., 2009). Similar image processing techniques are being trialled and developed under the GWFlood project to optimise detection of groundwater flood extents from RS data. A key element of the delineation and validation process is high-resolution topography. The Geological Survey Ireland, together with Coillte, have been collaborating on a pilot project to acquire Light Detection and Ranging (LiDAR) data over the last 2 years. The GSI is using LiDAR data to map karst features for groundwater resource and groundwater protection maps, as well as to enhance geological interpretation and geohazard (potential collapses, areas of instability) assessments. This is being supplemented by extensive LiDAR data collected by the Office of Public Works under the CFRAM Programme and by Ordnance Survey Ireland.

FLOOD MODELLING

There are two fundamental approaches to mathematical modelling of karst hydrogeological systems; distributive models and global models. Distributive models use theoretical concepts such as simplified aquifer geometry and hydrodynamic flow equations to simulate the hydraulic behaviour of karst aquifers (Kovacs and Sauter, 2007). Global models consider the karst aquifer as a transfer function, transforming the input signal (e.g. rainfall) into the output hydrograph signal (e.g. spring discharge, turlough level). Both approaches are being used within the GWFlood project to investigate the causative relationship between rainfall quantity, duration and flooding (flood frequency analysis), to reconstruct long-term hydrological records for key sites and to simulate the impacts of potential mitigation measures on flooding.

Over the last ten years, the Department of Civil, Structural and Environmental Engineering in Trinity College Dublin (TCD) have developed a distributive model of the complex karst system within the Gort Lowlands (Gill et al., 2013; McCormack et al., 2014). This model uses the Infoworks software package to simulate the groundwater-surface water flux between the active conduit network and a series of five interconnected turloughs (figure 4). As part of the GWFlood project, this model is being adapted and enhanced using detailed topography to simulate flooding events across the entire catchment under extreme conditions. Outputs from the research will provide valuable information to inform a Galway County Council and Office of Public Works (OPW)-led investigation of potential flood relief measures within the Gort Lowlands.

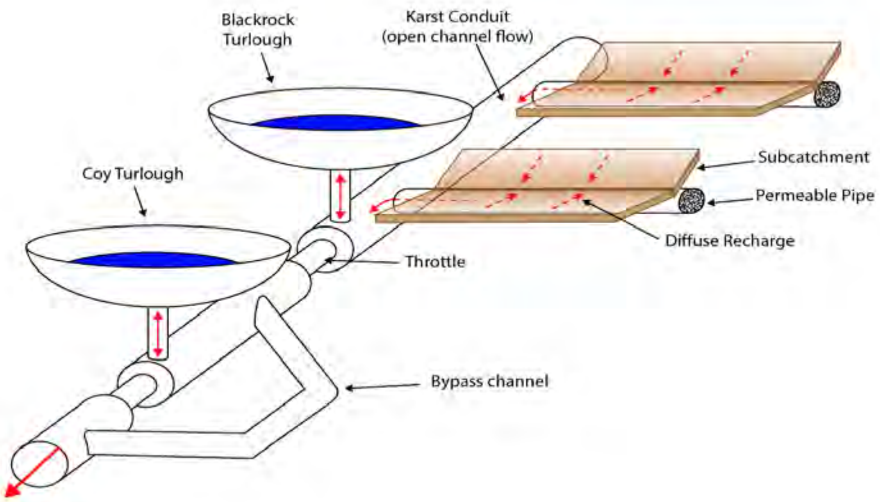

Fig. 4: Conceptual representation of the TCD Gort hydraulic model

For this reason, a flexible reservoir modelling methodology was developed to quantify hydrological functioning using readily derivable climatic variables. The model used regional rainfall and evapotranspiration data to produce wetland inundation time series and depth-duration curves for sites across a spectrum of flooding regimes. This approach, based on reservoir ("storage-release") modelling, is particularly well suited to the modelling of turloughs as they physically act as reservoirs for excess recharge during the winter months. In this approach the turlough is conceptualised as a reservoir with the same physical characteristics as the site being modelled (stage-volume-area relationships). The hydrological response of the reservoir is controlled by inflow and outflow relationships derived from analysis of the turlough water budget.

SUMMARY

The increased frequency, damage and disruption caused by groundwater flood events in recent years highlights the clear need for further research into the issue of groundwater flood prediction and risk assessment in karst regions. Due to the inherent complexity of karst groundwater systems and the lack of quantitative hydrological data available, the GWFlood project presents a unique opportunity to use a knowledge base gained over the last decade to contribute to flood risk management practices in Ireland. The project will provide the necessary high-quality data, mapping and analysis techniques required to inform future planning decisions, and so help to ensure the sustainability of vulnerable rural communities affected by groundwater flooding as well as the turlough habitats themselves. The project will influence policy and governance by giving decision makers more information on the drivers and mechanisms of groundwater flooding in Irish karst systems, and allow them to make scientifically-informed decisions for better outcomes within the Floods, Water Framework and Habitats Directives. The collaboration between the GSI and Trinity College Dublin will also strengthen existing partnerships between the institutions and open new applied geoscience research opportunities in the fields of groundwater flooding, geohazards, groundwater-surface water interactions and remote sensing.

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HOW UNDERSTANDING HYDROGEOLOGY CAN REDUCE RISKS ON LARGE LINEAR INFRASTRUCTURE PROJECTS

Catherine Buckley
ARUP

NOTES

SPACE-BORNE INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR) FOR DETECTING GEO-RISKS RELATED TO HYDROGEOLOGY

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NOTES

ARSENIC CONTAMINATION OF DRINKING WATER IN IRELAND: A SPATIAL ANALYSIS OF OCCURRENCE AND POTENTIAL RISK

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ABSTRACT

Arsenic in groundwater has become a global concern due to the health risks associated with elevated concentrations. The EU Water Framework Directive (WFD) calls for drinking water risk assessment for member states. The present study amalgamates readily available national and sub-national scale datasets on arsenic in groundwater in Ireland. However, due to the presence of high levels of left censoring (i.e. arsenic values below an analytical detection limit) and changes in detection limits over time, the application of conventional statistical methods inhibited the generation of meaningful results. In order to handle these issues several arsenic databases were integrated and the data modelled using statistical methods appropriate for non-detect data. Geostatistical methods were used to assess principal risk components of elevated arsenic related to lithology, aquifer type and groundwater vulnerability. Nearest-neighbour inverse distance weighting (IDW) and local indicator of spatial association (LISA) methods were used to estimate risk in non-sampled areas. Significant differences were noted between different aquifer lithologies, indicating that Rhyolite, Sandstone and Shale (Greywackes), and Impure Limestone potentially presented a greater risk of elevated arsenic in groundwaters. Significant differences occurred among aquifer types with poorly productive, locally important fractured bedrock and regionally important fissured bedrock aquifers presenting the highest potential risk. No significant differences were detected among different groundwater vulnerability groups. This research will assist management and future policy directions of groundwater resources at EU level and guide future research focused on understanding arsenic mobilisation processes to facilitate in guiding future development, testing and treatment requirements of groundwater resources.

Keywords: arsenic, groundwater, statistics, WFD, Ireland, geology

SESSION VII

DRINKING WATER SUPPLY SOURCES AND ORGANIC CARBON: IRISH GROUNDWATER VERSUS SURFACE WATER

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ABSTRACT

This paper presents a small snapshot of results for some natural organic matter (NOM) parameters in Irish surface waters and groundwaters. The works were completed over a number of years in the context of some surface water sources for existing public supply sites presenting issues in the context of Trihalomethane (THM) formation and compliance with Drinking Water Regulations. At some sites, groundwater was evaluated for its potential to provide a more sustainable source of water for public supply. Raw water parameters such as colour and organic carbon are useful indicators for the potential for a treated water to react with chlorine and create THMs at the point of supply to the consumer. Water characteristics are influenced by geographical factors. THM formation is influenced by water treatment plant processes, storage and distribution systems. The relative importance of any of the factors can only be derived from larger datasets and conclusions might change in the future. However, international research suggests that THM control will become more challenging in the context of global warming effects on raw water characteristics and increasing ambient temperatures in the future. Groundwater can provide a source of water that has a lower and more stable NOM characteristic than surface water. However, a robust and defensible evaluation of the potential for groundwater to provide a more sustainable source of water at a public supply site might require construction of the abstraction point as a ***completed*** *'Production Well', to a standard such as EA Advice Note 14 (2013), so that surface influences and potential sources of organic matter are sealed off for the evaluation.*

INTRODUCTION

Natural Organic Matter (NOM) is of significance to the supply of drinking water to the public because of its interaction with water treatment processes. Chlorine and NOM parameters interact and create a disinfection by-product (DBP) of organic chemicals grouped and labelled Trihalomethanes (THMs). Most of the public water supply sources in Ireland abstract water from rivers and lakes (surface waters). Even when 'groundwater' is the source of the water supply, influences from the surface can contribute particulate and organic matter. Groundwater having an organic matter content is, in my experience, more to do with borehole construction rather than the groundwater's characteristic. Of course there are exceptions in karst hydrogeology and landscape linkages.

The information presented in this paper is not a wide data record for an extensive range of sites nor a long term research project. The results presented are a snapshot for various locations around the country at existing public water supplies. Groundwater was evaluated for its potential to provide a more sustainable source of water for public supply at some sites that currently rely on surface water.
The Drinking Water Regulations (S.I. 122 of 2014) prescribe quality standards to be applied in the provision of potable water public supply consumers in Ireland, the relevant supervision required and the enforcement procedures in relation to the supply of drinking water, including sampling frequency requirements, methods of analysis, compliance monitoring and the provision of information to the consumers. The Drinking Water Regulations set a limit of 100 ug/l on the Total THM concentration. However, water treatment engineers and the international community of scientists that concern themselves with THMs do not like to consider the 100 ug/l THM concentration as a target. Rather, it is preferred that the THM concentration is a fraction of the Drinking Water Regulation limit. For

most of the public supplies THM concentration is not a problem because the source does not present a challenging NOM characteristic for the water treatment plant. Unfortunately at some sites, and often only at some times of the year, THM formation is a management issue. Under the Drinking Water Regulations Irish Water has the responsibility to provide potable water to public supply consumers and water treatment processes are part of the equation.

WATER TREATMENT, DISINFECTION & TRIHALOMETHANES

There are many excellent information resources relating to the topic of water treatment and THMs. Amongst other EPA Advice Notes of significance, which are available at http://www.epa.ie/pubs/advice/drinkingwater/, I suggest readers refer to EPA (2012) Advice Note No 4. Version 2: Disinfection By-Products in Drinking Water and the scientific report on the determinants of THMs in drinking water sources reported by Valdivia-Garcia *et al.*, (2016).

"EPA Advice Note No. 4: "Disinfection by-products are formed by the reaction of chemical disinfectants with by-product precursors. Natural organic matter (usually measured as total organic carbon (TOC)) and inorganic matter (bromide) are the most significant disinfection by-product precursors. All commonly used chemical disinfectants (e.g. chlorine, chlorine dioxide, chloramines and ozone) react with organic matter and/or bromide to varying degrees to form different disinfection by-products (DBPs). Trihalomethanes (THMs) are one of the most common disinfection by-products in Ireland".

With respect to water treatment, Irish Water (2016) summarises that DBP concentrations vary seasonally and are typically greatest in the summer and early autumn for several reasons:

- The rate of DBP formation increases with increasing temperature;
- The nature of organic DBP precursors varies with season; and
- Due to warmer temperatures, chlorine demand may be greater during summer months requiring higher dosages to maintain disinfection.

With respect to the factors creating precursors for THMs, Valdivia-Garcia et al., (2016) suggest that climate and geographical location especially when source waters are subject to marine influences, high and-or regular precipitation, and elevated levels of organic matter.
Therefore, we can summarise as follows:

- Geographic (soils, geology and location) and climatic factors (temperature & rainfall) are key to THM formation.

- Surface water, especially lakes, are subject to temperature effects that manifest in NOM turnover in summers presenting issues in the management of water treatment plant processes.

In a joint position statement on drinking water and Trihalomethanes, the HSE & EPA (2011) presented as follows:

> "Disinfection is a critical part of drinking water treatment and is fundamental to preventing the spread of waterborne infectious diseases. The use of disinfectant chemicals can result in the formation of disinfection by-products (DBPs). Chlorination is the most common disinfection method used in Ireland and chlorine use is regulated primarily to minimise the formation of DBPs, the most common of which are trihalomethanes (THMs). THMs are a group of organic chemicals, often present in drinking water and formed when chlorine reacts with naturally occurring organic matter in raw water. Chlorine is a powerful oxidising agent and it breaks down complex organic molecules which are the colouring agents of water, forming smaller reactive entities. These entities react with chlorine to form THMs. There is a direct relationship between the degree of colour in the water prior to chlorination and the concentration of THMs after chlorination. THMs are a group of four chemicals – chloroform, bromoform, dibromochloromethane and bromodichloromethane. Chloroform tends to be

present in the greatest concentration. Total THMs is a parameter on the chemical table in the 2007 Drinking Water Regulations. A further group of chlorine associated DBPs, haloacetic acids (HAAs), are of increasing concern but are not included in the 2007 drinking water regulations although they may well be included in the future regulations. Because most water supplies in Ireland are surface water sources and some of our groundwater sources may be influenced by surface water, raw water is likely to contain high levels of particulate and organic matter. This can be much greater after heavy rainfall or flooding. Trihalomethanes are formed when there is either inadequate pre-treatment of the water and/or poor control over the disinfection process itself. THM formation is dependent on several variables; the concentration and nature of the organic material in the raw water, chlorine contact time, the residual chlorine concentration in the water and the pH and temperature of the water. Optimum filtration and coagulation before disinfection is therefore important in preventing the formation of THMs. Chlorine is used not only as a primary disinfectant in water treatment but is also added to provide a stable disinfectant residual to preserve the quality of the water throughout the distribution network. While this characteristic of chlorine makes it most suitable as a disinfectant it also means that it is more prone to DBP formation because it has more contact time with organic matter in the water that was not removed during treatment (coagulation and filtration). Additional chlorine may be added in order to maintain an adequate residual concentration throughout the distribution system particularly at end points. Temperature and pH of drinking water vary across supplies and from season to season. Optimum control over all of these factors is necessary to keep THMs to a minimum."

EPA (2014) explains the significance of Trihalomethanes as a parameter of the Drinking Regulations as follows:

"Trihalomethanes (THMs) are derivatives of the simplest organic compound - methane, CH4 - in which 3 of the hydrogen atoms are substituted by halogen atoms. The principal halogens are fluorine (F2), chlorine (Cl2), bromine (Br2) and iodine (I2), but while many combinations are theoretically possible, the term trihalomethanes is applied to four specific compounds containing only chlorine and/or bromine as the halogen elements. The four compounds are chloroform (CHCl3), bromodichloromethane (CHBrCl2), dibromochloromethane (CHBr2Cl) and bromoform (CHBr3). As a powerful oxidising agent, chlorine also breaks down the complex and inert organic molecules which are the colouring agents of the water, forming smaller, reactive entities. These entities react with chlorine (and with bromine derived from the oxidation by chlorine of bromide naturally present) to form the THM compounds, the most abundant of which is chloroform (CHCl3). There is thus a fairly straightforward relationship between the degree of colour in the water prior to chlorination and the quantities of THMs present following chlorination. If colour is present at the point of chlorination, THMs are likely to be formed. THM compounds are undesirable in drinking water for two reasons. Firstly, the actual compounds themselves may pose a hazard to the health of the consumer if present in excessive amounts. Chloroform is classified by IARC as a possible carcinogen although the Committee on Toxicology has concluded "Problems remain in the interpretation of published studies. These include the small relative risks recorded, the possibility of residual confounding, and the problems with exposure assessment. They concluded that the evidence for a causal association between cancer and exposure to chlorination by-products is limited and any such association is unlikely to be strong". Secondly, the presence of the THM group may be an indicator of the possible presence of other organic by-products of chlorination in trace amounts. The WHO advises that "In controlling trihalomethanes, a multistep treatment system should be used to reduce organic trihalomethane precursors, and primary consideration should be given to ensuring that disinfection is never compromised".

In order to inform and provide an engineering justification for the design of water treatment systems, Irish Water also has detailed guidance on the evaluation of water treatment processes in the context of NOM characteristics of raw waters (Irish Water, 2016): "Raw source waters contain both humic and non-humic organic substances and groupings. NOM can be subdivided into a hydrophobic fraction composed of primarily humic material, and a hydrophilic fraction composed of primarily fulvic material." Irish Water (2016) suggest the use of surrogates to assess NOM including the following:

- Total (TOC) and dissolved organic carbon (DOC);
- Specific ultraviolet light absorbance (SUVA), which is the absorbance at 254 nm wavelength (UV254) divided by DOC (SUVA = (UV-254/DOC)*100, in l/mg-m).
- THM formation potential (THMFP) - a test measuring the quantity of THMs formed with a high dosage of free chlorine and a long reaction time;
- Ultra Violet Transmission (UVT) & Ultra Violet Absorbance (UVA).

EVALUATION CRITERIA

In our evaluations at public water supply sites in Ireland, we considered that

- Raw and pure groundwater would typically have a TOC concentration < 2 mg/l and surface water would typically have a > 2 mg/l TOC concentration.

- A raw source water having a TOC concentration between 4 and 6 would have THM forming potential above the 100 ug/l limit.

- A SUVA figure >4 suggests a "Major propensity to form THMs". SUVA in excess of 4 is indicative of predominately humic hydroscopic material which has a major propensity for THM formation unless removed by a treatment process. SUVA lower than 2 is generally indicative of waters with low THM formation potential (Ryan Hanley, 2012).

- Although opinions and guidance on the significance of surrogate parameters change, UVA has been considered useful for assessing the presence of TOC/DOC because organic carbon constituents consists of humic substances, which contain aromatic structures that absorb light in the UV spectrum. Of the TOC content, DOC content can be 90%.

SOME EXAMPLES FROM SITES STUDIED & DATA

1. **Groundwater as a source of public supply from a properly constructed water supply well in east Galway**.

   NOTE: Information for this site is presented in order to provide a baseline characteristic for groundwater from a BH that is correctly completed to EPA Advice Note 14 (2013) standard. This Public Supply (PS) site did not present for THM issues. This PS site had other issues relating to a poorly constructed borehole and intermittent turbidity problems that resulted in the scheme being placed on Boil Notice.

Table 1 East Galway PS BH Hydrogeology (Site Information, EPA, 2010).

GEOLOGY	Soil:	Deep well drained mineral (BminDW)			Subsoil Permeability:	Low
	Subsoil:	Tills (diamictons) (TLs)				
	Bedrock:	Dinantian Upper Impure Limestones				
HYDROGEOLOGY	Aquifer Category:	LI	Vulnerability at Monitoring site:	Extreme	Flow Regime:	Poorly productive

Table 2 Groundwater's THM precursors: East Galway PS BH completed to EPA Advice Note 14 Standard.

RAW Untreated Groundwater: East Galway PS BH: 8 day Pump Test April 2016				
Date	19/04/2016	20/04/2016		
Time (clock)	6.45 pm	9.30am		
Time since start of Test (hrs)	128.75	143.5		
Total Groundwater Volume Abstracted (m3)	1159	1292		
Abstraction Rate at Time of Sampling (m3/hr)	10m3/hr	10.4 m3/hr		Drinking Water Regulation 2014 Parametric values (SI 122 of 2014)
Required Abstraction Rate for PS	8m3/hr	8m3/hr		
Suspended Solids	<2	<2	mg/l	not specified
Turbidity	0.7	0.4	N.T.U.	acc. to consumers
UV Transmission (UVT) @ 254nm	94.3	94.8	%	not specified
Colour, apparent	<4	<4	mg/l Pt Co	acc. to consumers
TOC	1.87	2.31	mg/L	no abn. Change
DOC	1.81	2.11	mg/l	not specified
SUVA	1.38	1.0	L/mg-m	not specified

2. **Searching for groundwater as an alternative to a lake source of public water supply for an island off the coast of Mayo**;

NOTE: there were three water characterisation sampling events on the island: October 2015, January 2016 & June 2016. The Public Water Supply requirement is 30m^3/d. The project brief was to evaluate alternative sources of water that could be used to supply the public.

Table 3 Island off the coast of Mayo: THM precursors and results of jar testing.

sampling event (June 2016)			LAKE Source	Groundwater Spring Discahrges		
	Test	Units	Lake Source Raw Water @ WTP inlet	Natural Spring Discharge Giants Tumble. 26/06/16	OT Well hand Dug Well Corn Hill. 26/06/16	School Spring. 26/06/16
RAW WATER Laboratory results for general characterisation of Colour, NTU, TOC, DOC etc.	Colour	mg/l Pt Co	83.3 mg/l Pt Co	17.3 mg/l Pt Co	6.5 mg/l Pt Co	26.2 mg/l Pt Co
	Turbidity	N.T.U.	4.1 N.T.U.	0.3 N.T.U.	0.2 N.T.U.	0.8 N.T.U.
	pH	pH Units	6.8 pH Units	7.2 pH Units	6.4 pH Units	6.6 pH Units
	Conductivity @20C	uS/cm	372 uS/cm	323 uS/cm	394 uS/cm	408 uS/cm
	Chloride	mg/l	89.3	78.9	95.4	83.6
	TOC	mg/l	5.7 mg/L	3.21 mg/L	4.22 mg/L	2.08 mg/L
	DOC	mg/l	5.16	3.03	3.37	2.04
	UV Absorption	(UVA) @ 254nm	0.134	0.100	0.057	0.046
	Alkalinity Total	mg/l CaCO3	35 mg/l CaCO3	26 mg/l CaCO3	34 mg/l CaCO3	65 mg/l CaCO3
TTHM Formation Potential Laboratory Simulation						
Laboratory Chlorine Dosed @ 5mg/l & Incubated @ 16 oC. Chlorine Results @ 15mins, 2hrs & 24 hrs.	(15min post chlorination)	mg/l	2.50	3.25	3.45	3.20
	Chlorine, free (2hrs post chlorination)	mg/l	1.90	2.00	2.95	2.40
	(24hrs post chlorination)	mg/l	0.68	1.67	2.00	1.89
TTHMS @ 6hrs post chlorination						
Laboratory Results for TTHMs @ 6 Hours	**Trihalomethanes - Total**	**ug/l**	**162.3**	**137.3**	93.3	71.6
	Chloroform	ug/l	88.2	55.3	19	13.9
	Bromoform	ug/l	1.8	3.8	10.2	8.3
	Dibromochloromethane	ug/l	20.9	30.1	34.6	27.9
	Bromodichloromethane	ug/l	51.5	48.1	29.5	21.5
TTHMs @ 24hrs post chlorination						
Laboratory Results for TTHMs @ 24 Hours	**Trihalomethanes - Total**	**ug/l**	**207.9**	**172.8**	**106.1**	83.6
	Chloroform	ug/l	120.7	77.9	22.4	15.4
	Bromoform	ug/l	1.8	3.8	11.9	9.6
	Dibromochloromethane	ug/l	24.1	34.3	38.6	33.4
	Bromodichloromethane	ug/l	61.2	56.7	33.2	25.2

3. **Evaluating groundwater as an alternative to a lake source of public water supply in the midlands**.

Table 4 Selection of laboratory results: Midlands drilling, Trial wells, groundwater spring and PS lake source.

		Deep Limestone BH: WS @ 19m & 54m bgl (BH TD 74m bgl) (TRIAL Construction, both Water strike zones open)			Gravel WS @ 19m bgl (BH TD 20m bgl)		Natural Local Spring Discharge in a BOG				
Sample ID		TW1 22/09/16	TW 1 26/9/16	TW1 4/10/16	TW4 26/09/16	TW4 4/10/16	Local Large Spring 22/09/16	Local Large Spring26 /09/16	Local Large Spring 4/10/16	Existing Source Raw Lake Water to PS WTP tap 22/09/16	Existing Source Raw Lake Water to WTP Tap. 26/09/16
SELECTION OF Laboratory RESULTS											
Alkalinity Total	mg/l CaCO3	370	375	357	360	339	391	345	384	180	198
Total Hardness (Kone)	cfu/100ml	276	338	<20	314	<20	314	343	402	195	179
Chloride	mg/l	14.4	14.2	14.2	14.4	14.4	12.7	11.7	11.5	12.1	11.5
Colour, apparent	mg/l Pt Co	**383**	**405**	**386**	**396**	**451**	21.8	51.6	16.7	193	169
SUVA		2.15	2.24	3.12	1.82	1.96	2.78	3.58	3.16	5.74	5.40
TOC	L/mg-m	3.7	3.5	3.49	3.16	3.59	3.79	4.63	3.64	16.3	15.5
DOC	mg/L	3.44	3.3	3.33	3.13	3.42	3.6	4.61	3.16	15.9	15.3
Turbidity	mg/l CaCO3	27.5	33.4	33.0	33.2	53.2	0.9	2.9	1.0	1.4	1.9
UV Absorption (UVA) @ 254nm	N.T.U.	0.074	0.074	0.104	0.057	0.067	0.100	0.165	0.100	0.912	0.826
UV Transmission (UVT) @ 254nm		53.6	58.8	52.9	62.4	56.1	77.3	62.3	77.9	10.7	13.5
		TW 1 = Deep Limestone BH (Water Strikes @ > 50m bgl)			TW 4 = Adjacent Shallow Gravel BH		Spring			Lake	

4. **Groundwater borehole examples from the most southerly inhabited island of Ireland.**
Table 5 Groundwater borehole results from Ireland's most southerly inhabited island's well field.

Parameter	BH 1 (14% of total CRA yield)						
Sample Date	13/06/16	14/06/16	15/06/16	16/06/16	17/06/16	26/10/16	26/10/16
Abstraction Rate	Unknown	Unknown	Unknown	Unknown	Unknown	27m³/d	27m³/d
TOC (mg/l)	1.18	1.086	1.13	1.086	1.108	<1	<1
DOC (mg/l)						<1	<1
UVA_{254} (cm^{-1})	0.006	0.002	0.004	0.002	0.003	0.002	0.003
SUVA (L/mg.m)	<0.5	<0.18	<0.35	<0.18	<0.27	<0.2	<0.3

Parameter	BH 1A(6% of total CRA yield)			BH 3a(6% of total CRA yield)			BH 4A(42% of total CRA yield)	
Sample Date	28/07/16	26/10/16	27/10/16	13/10/16	18/10/16	20/10/16	28/07/16	18/10/16
Abstraction Rate	Unknown	11.5m³/d	7m³/d	58m³/d	9m³/d	12m³/d	4.8m³/hr	5.3m³/hr
TOC (mg/l)	1.47	1.25	1.08	2.6	1.68	2.5	<1	3.58
DOC (mg/l)		1.06	<1.0	2.5	1.67	2.37		3.43
UVA_{254} (cm^{-1})	<0.005	0.015	0.009	0.071	0.031	0.055	0.005	0.133
SUVA (L/mg.m)	<0.5	1.41	<0.90	2.84	1.85	2.32	<0.5	3.87

Table 5 (cont'd) Groundwater borehole results from Ireland's most southerly inhabited island's well field.

Parameter	BH 5(21% of total CRA yield)							
Sample Date	13/06/16	14/06/16	15/06/16	16/06/16	17/06/16	28/07/16	13/10/16	18/10/16
Abstraction Rate	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	44m^3/d	Unknown
TOC (mg/l)	1.79	2.02	2.066	2.066	2.089	1.88	2.38	1.73
DOC (mg/l)							2.31	1.72
UVA_{254} (cm^{-1})	0.033	0.043	0.045	0.045	0.046	0.031	0.048	0.04
SUVA (L/mg.m)	1.84	<2.13	<2.18	<2.18	<2.2	<1.65	2.09	2.32

Parameter	BH 6A(11% of total CRA yield)		
Sample Date	13/10/16	18/10/16	19/10/16
Abstraction Rate	33m^3/d	26m^3/d	22m^3/d
TOC (mg/l)	1.01	<1	1.1
DOC (mg/l)	<1	<1	<1
UVA_{254} (cm^{-1})	0.005	0.008	0.018
SUVA (L/mg.m)	0.5	<0.8	<1.8

MY EXPERIENCE

A properly constructed water supply well that is completed to EPA Advice Note 14 (2013) or a clean, gravelled, housed, spring emergence point can provide a more sustainable source of water, for the long term, than some of the existing surface water sources. In particular, I think some lakes will show signs of over-abstraction. We have evidence that a water supply well that is properly constructed in the subsurface, even in a peaty catchment with some visually significant local organic discharge pressures in close proximity at ground level, can provide a raw groundwater that has a low organic carbon, colour and turbidity characteristic. At that same PS site, an improperly constructed borehole presented management challenges for many years and resulted in the scheme being on Boil Notice for a significant and problematic amount of time. Also of note is that the interaction of the various influencing factors are complex. Marine influences are cited as significant. However even though Cape Clear is an island, its geology and southerly position might be one reason why its pre-cursor characteristics and resultant THM concentrations at the Point of Supply are low.

CONCLUSIONS

THM formation in treated water is related to the NOM characteristic of raw water. Analysis of raw water for parameters such as colour and dissolved organic carbon are useful indicators for the potential for a treated water to react with chlorine and create THMs at the point of supply to the consumer. Raw water characteristics are influenced by geographical location such as subsoils, bedrock geology and climatic factors. THM formation potential is a function of both the raw water characteristic, operations at the water treatment plant, water storage and the distribution system. The relative importance of any of the factors can only be derived from larger datasets and conclusions might change in the future. However, international research reported on a larger dataset of water treatment plants (Valdivia-Garcia et. al., 2016) concludes that THM control will become more challenging in the context of global warming effects on raw water characteristics with increasing ambient temperatures in the future. Groundwater can provide a source of water that has a lower and more stable NOM characteristic than surface water. However, a robust and defensible evaluation of the potential for groundwater to provide a more sustainable source of water at a public supply site might require construction of the abstraction point as a **completed** 'Production Well', to a standard such as EA Advice Note 14 (2013), so that surface influences and potential sources of organic matter are sealed off for the evaluation.

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IDENTIFYING SOURCES OF NATURAL ORGANIC MATTER & TRIHALOMETHANES: CASE STUDY FROM A GROUNDWATER SPRING IN A KARST REGION IN THE WEST OF IRELAND

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ABSTRACT

A drinking water supply in the west of Ireland with elevated trihalomethane concentrations was investigated. The supply was sourced from a spring in a vulnerable karst region. Sources of natural organic matter were traced from the potential catchment, through the treatment process and into the distribution network and THM occurrence was investigated with respect to natural organic matter character. Principal component analysis highlighted that the raw water quality was most similar to a nearby turlough and a sister spring on the majority of sampling occasions however, in episodic rainfall events all sites had similar character. Raw water DOC concentrations were highly variable over the study period. PARAFAC identified a four component model and according to previous classifications consisted of a humic-like terrestrial organic matter, ubiquitous to freshwater, composed of high molecular weight and aromatic organic compounds; a humic-like, terrestrial delivered reprocessed organic matter; a second humic like terrestrial delivered organic matter; and a protein-like microbial delivered organic matter. Ozone and GAC filtration had poor efficacy in treating NOM with similar DOC concentrations observed before and after treatment. The most prominent fluorescent component in the treated water was the humic-like, terrestrial delivered reprocessed organic matter. THMs exceeded the parametric value of 100 µg L^{-1} on eleven out fifteen sampling occasions. Spearman rank correlations highlighted significant correlations among DOC, UVA_{254} SUVA, humic like PARAFAC components, TN, chloroform, and total THMs.

INTRODUCTION

More than 2 billion people depend on groundwater for their daily water use and in many parts of the world groundwater bodies are considered the most important and safest sources of drinking water (Menichini et al., 2015). However, groundwater is particularly vulnerable in areas composed of carbonate rocks, i.e. karst areas and human activities threaten to contaminate these groundwater resources far more easily than is the case for other types of aquifers. Presence of natural organic matter (NOM) in raw drinking water poses one of the greatest challenges for drinking water treatment owing to problems such as membrane fouling, requirement for enhanced coagulation, energy consumption, transport of pesticides and pharmaceuticals and formation of disinfection by-products (DBPs). DBPs are formed when natural water is disinfected to control microbial contaminants during the treatment of drinking water. Trihalomethanes (THMs) are the most prominent class of halogenated DBPs in treated water (Krasner et al., 1989), and the only one regulated by European Union Drinking Water Regulations (EU, 2014). Adequate disinfection takes precedence however, and should never be compromised in attempting to meet guidelines for THMs; the World Health Organisation recommends that THM levels in drinking water be kept as low as practicable (WHO, 2011).

Catchment delineation or identification of the 'zone of contribution' (ZOC) is crucial to protecting groundwater drinking sources, however, determination of a rigorous and scientific methodology for all types of aquifer systems is very difficult in practicality (Menichini et al., 2015). The main objective of this study was to trace the sources of NOM and investigate the presence of THMs in a groundwater drinking water supply in a vulnerable karst region.

Materials and Methods

The Study Area was chosen as it represents a spring source (SS) located in a vulnerable karst area that has a history of elevated THM concentrations. The ZOC for the SS was mapped as part of a desk study (EPA, 2011) and determined to be 1.41 km^2. The treatment train at SS consisted of ozonation, Granular Activated Carbon (GAC) filtration (CARBSORB®), UV chlorination and disinfection. Water samples were collected at five locations in a 4 km^2 vicinity of the SS (a wetland; a turlough; a small tributary; a series of sister springs adjacent to the raw water abstraction (SisterSpring); and at the outlet of a sewage treatment plant (WWTP)), in addition to three locations along the treatment process train of the SS (raw water, post-ozone and post-GAC filtration) and nine locations in the distribution network (a public water tap, before and after two reservoirs and at four network extremities; total n=17).

To further investigate the ZOC, a staff gauge was installed at the SisterSpring. A rating curve was developed using spot flow measurements at a range of flows which established that while the SS had a daily discharge of ~600 m^3 d^{-1} the SisterSpring had a daily discharge of ~19,000 m^3 d^{-1}. Using topography, known tracers and the integration of recharge coefficients a reasonable and justifiable catchment size for the combined SS and SisterSpring was estimated to be ~24 km^2, 16-fold greater than that reported for the SS (EPA, 2011).

Monthly water samples were collected and analysed for DOC, UVA, and TN. Fluorescence excitation emission matrices (EEMs) were obtained and modeled using PARAFAC (multi-way data analysis using parallel factor analysis, Stedmon et al., 2003) to identify DOC character and sources. Water samples were collected from the catchment sites for determination of major cations and at six locations in the network for THMs. Major cation and trace metal analyses were performed using inductively couples plasma mass spectrometry (ICP-MS) (PerkinElmer ELAN DRCe, Waltham, USA) in a class 1000 (ISO class 6) cleanroom in the Chemical Monitoring Facility at NUI, Galway. THM analysis (chloroform, bromoform, dibromochloromethane and bromodichloromethane) was carried out by an external accredited laboratory (CLS Connemara, Galway, Ireland). Principle component analysis was used to investigate the relationships between hydro-chemical indicators and study locations.

RESULTS AND DISCUSSION

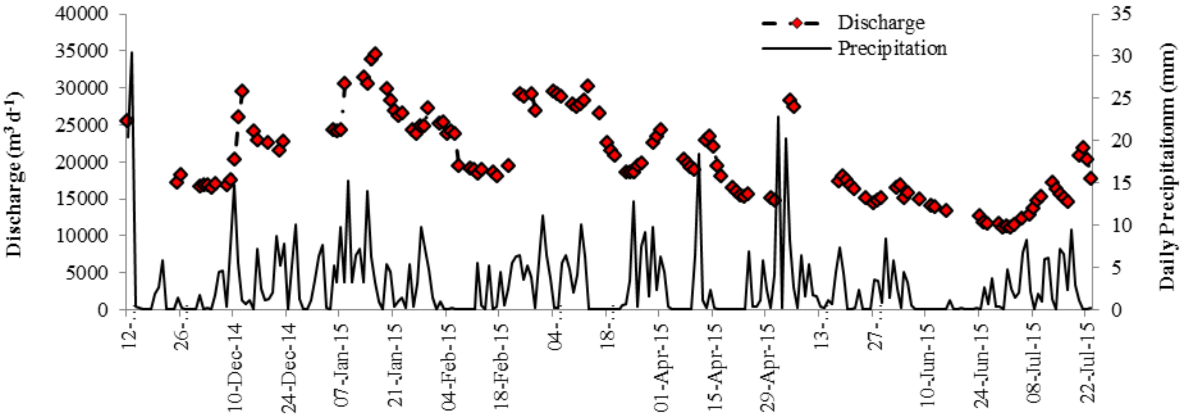

Figure 1 Mean estimated stream discharge (m^3 d^{-1}), from the SisterSpring over the observation period (12/11/2014 – 22/07/2015), with corresponding daily total precipitation (mm).

Mean estimated stream discharge, from the SisterSpring was 20,559 m^3 d^{-1} (Figure 1). The maximum change in recorded water level over the observation period was ~100 mm throughout the winter and

50 mm through the summer. Instantaneous discharge response to rainfall peaks suggests that there is no major storage deep in the groundwater/ bedrock system. DOC concentrations from the SS raw water varied between 3.84 - 11.40 mg L^{-1} with an average of 5.95 mg L^{-1} (Figure 2). An overall seasonal trend could be observed with DOC concentrations increasing by 2 mg L^{-1} from summer to winter with the exception of July and August 2015. The highest DOC concentrations were observed in July and August 2015 following a drought period in June 2015. DOC concentrations plotted against temperature showed no correlation whereas, DOC concentrations plotted against precipitation gave a strong positive correlation (R^2 = 0.76).

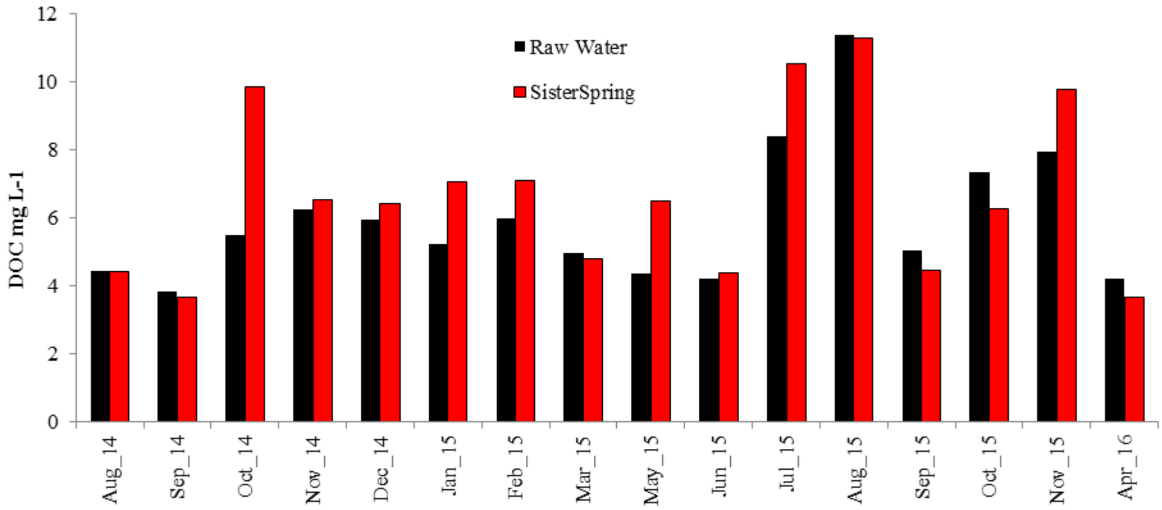

Figure 2 Dissolved organic carbon concentrations from water samples taken at the SS raw water abstraction and adjacent SisterSpring.

DOC concentrations from the catchment sites varied with the Wetland site showing the highest concentrations (20.46 mg L^{-1}, 09/2015), and the SS raw water, the lowest (Figure 3). DOC concentrations observed in the raw water were indicative of groundwater strongly influenced by the occurrence of surface karst features (Pronk et al., 2006). In comparison to other catchment sites, the adjacent Sister Spring and the Turlough site ~4 km away had the most similar DOC concentrations to the raw water. In lowland karst regions underground water flow occurs through the epikarst and consequently discharges to springs, turloughs and streams and as a result, surface and underground flow systems are highly connected (Pavlis and Cummins, 2014a). Temporal variation was more evident at the surface water sites, demonstrated by the high standard deviations at the wetland and tributary sites (Figure 3).

Principle component analysis on the 5 catchment sites and the Raw Water over the study period identified three groupings of samples: 1) the first dominated by Wetland samples and defined by high DOC, 2) the second by Raw water, Turlough and Sister Spring samples were defined by low DOC, high magnesium and calcium, and 3) the third by the WWTP samples which were defined by higher zinc, iron, selenium, silicon and sodium. DOC, considered to be of external origin, is introduced into the aquifer system via infiltration from the surface and is related to water transit time (Pavlis and Cummins, 2014b). Ca and Mg are considered to be of internal origin (bedrock dissolution) and Na and Se are related to anthropogenic activities that mostly have external origin (Pavlis and Cummins, 2014b). Raw water samples were most similar to the SisterSpring and Turlough sites except for on three occasions following high rainfall when all sites became quite similar when the water table rose and lands became flooded.

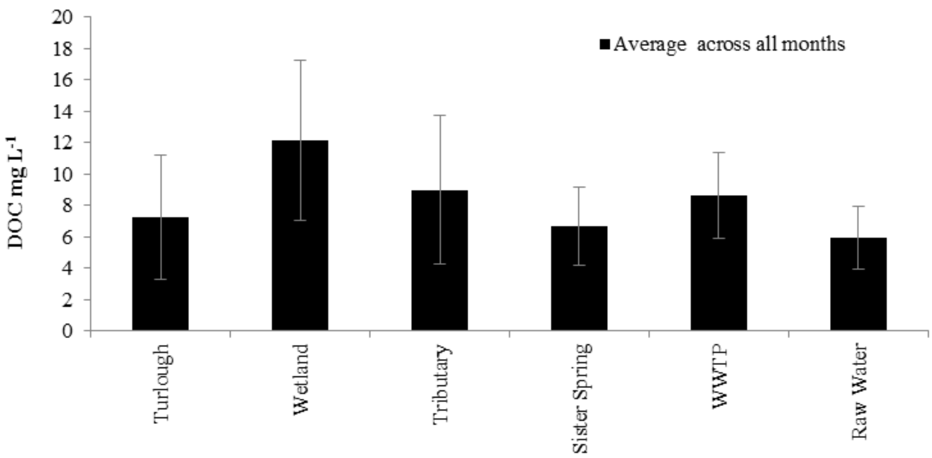

Figure 3 Dissolved organic carbon concentrations from the five locations in a 4 km^2 vicinity of the SS spring and the SS spring/ Raw Water over the duration of the study period.

A four component model (Comp 1-Comp 4) was established and according to previous classifications Comp 1 consisted of humic-like terrestrial organic matter, ubiquitous to freshwater, composed of high molecular weight and aromatic organic compounds; Comp 2 consisted of humic-like, terrestrial delivered reprocessed organic matter; Comp 3 consisted of humic like terrestrial delivered organic matter; and Comp 4 consisted of protein-like microbial delivered organic matter (Figure 4).

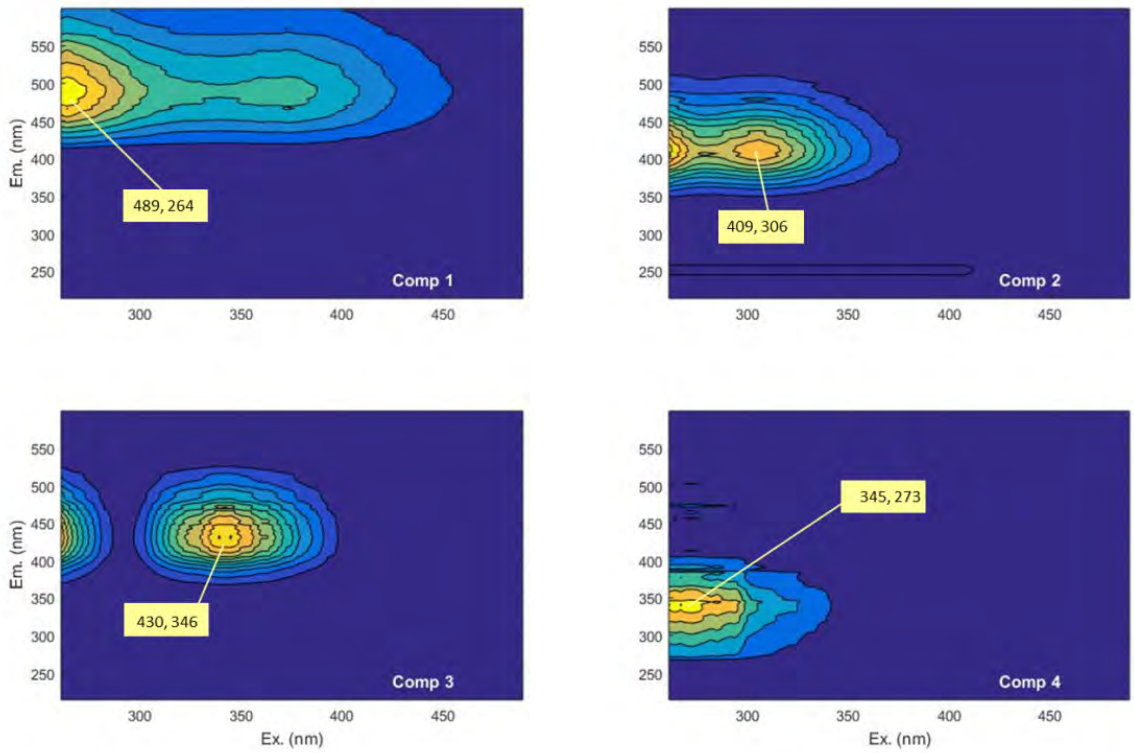

Figure 4. Loading values for the 3 PARAFAC components with Excitation (nm) on the x-axis and Emission (nm) on the y-axis.

All four components are commonly reported in surface and treated water (Shutova et al., 2014). In all water samples taken from the catchment sites, Comp 1 and Comp 2 had higher fluorescence intensities than Comp 3 and Comp 4. All sites exhibited contrasting organic matter properties. Specifically, the Turlough and SisterSpring samples experienced the highest variability in concentrations of Comp 1 and Comp 2 in contrast to the Raw water samples which tended to be more stable for all components. The two surface water-fed sources (i.e. the Wetland and the Tributary) had higher concentrations of Comp 1 than Comp 2 compared with the four groundwater sampling locations highlighting a lengthier residence time of the water and increased processing of organic matter in the groundwater samples. The WWTP had the highest range of fluorescence intensities for Comp 4. Comp 4 was associated with protein-like sewage-derived material presumably due to the production of NOM from microbial activity (Kraus et al., 2010). The WWTP was a constructed wetland and catchment drainage is via a series of small streams that disappear underground via a swallow hole located approximately 500 m east of the site.

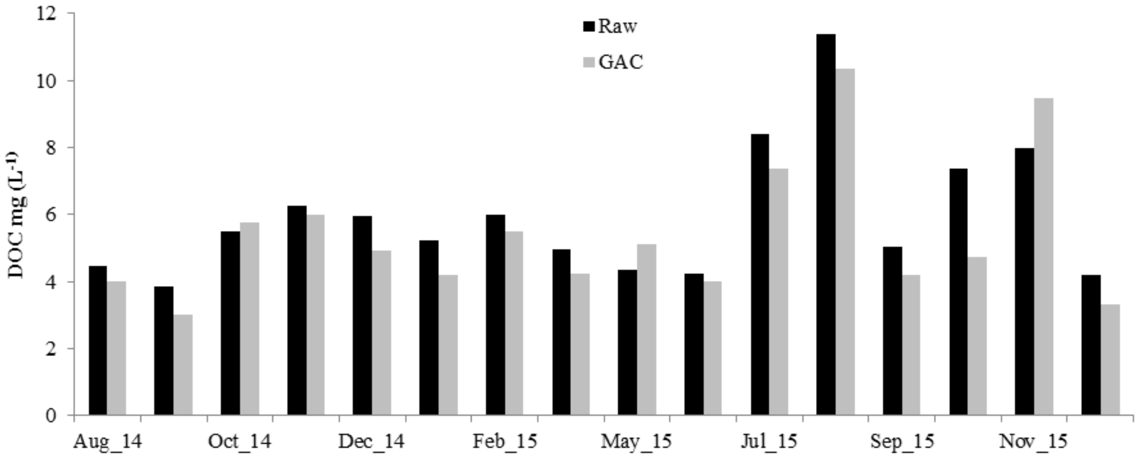

Figure 5. DOC measured at the Raw Water and post GAC.

Raw and treated water DOC concentrations had similar means and ranges suggesting limited removal of NOM (Figure 5). Ozone treatment sufficiently decreased the hydrophobic molecules with an average reduction in UVA_{254} in the range of 0.0040 – 0.1486 nm (Sohn et al., 2007) (Figure 6). GAC removal efficiency of NOM has been shown to be most dependent on regeneration (Matilainen et al., 2005) and the GAC filter in this study had never been regenerated.

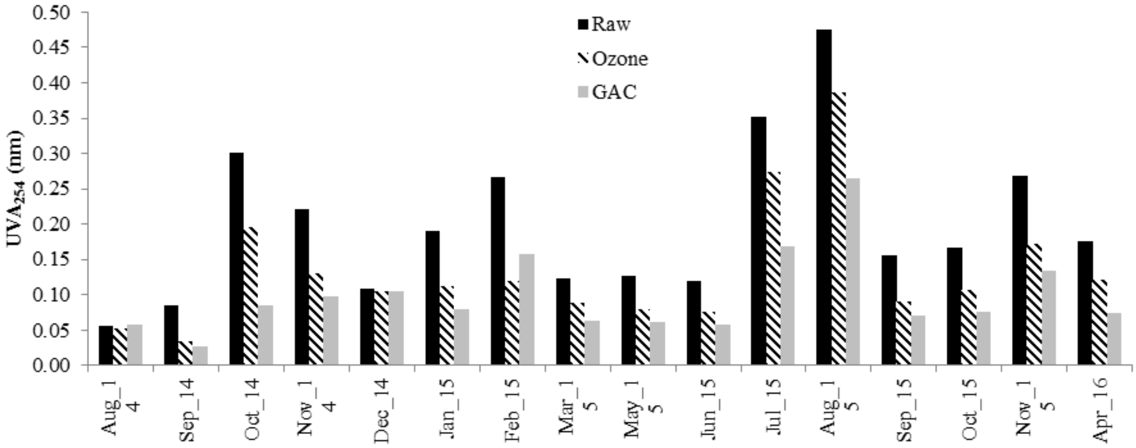

Figure 6. UVA_{254} measured at the raw water, post ozone and post GAC sampling points.

Average SUVA for raw water was 3.2 L mg^{-1} m^{-1}, an indication of NOM of moderate aromaticity and while GAC has been shown to be most effective for removal of NOM in this range (Matilainen et al., 2005) the ozone treatment altered the character of the NOM reducing the SUVA to an average of 2.0 mg L^{-1} prior to GAC filtration. The average SUVA in the finished water was 1.8 L mg^{-1} m^{-1}, which is typical of NOM with low aromaticity (SUVA<2 L mg^{-1} m^{-1}). On five occasions SUVA was greater than 2.0 L mg^{-1} m^{-1}, the parametric value specified above which THMs are likely to form (EPA, 2012).

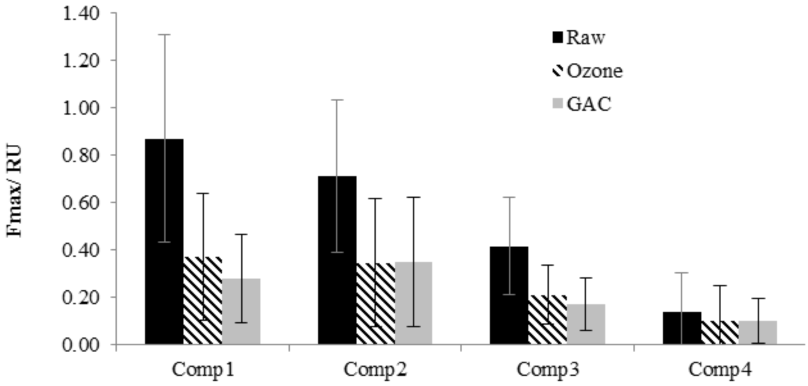

Figure 7 Fluorescence intensities at the raw water, post-ozone and post-GAC sampling points.

Fluorescence intensities (FI) were higher for terrestrial and ubiquitous humic like Comp 1 in the Raw water (Figure 7). Ozonation decreased the FI of all humic like components (Comp 1, Comp 2 and Comp 3). GAC marginally decreased the FI in the terrestrial derived humic like components however was ineffective for the terrestrial delivered reprocessed organic matter (Comp 2) and the protein like microbial delivered organic matter (Comp 4). These findings are consistent with previous studies (Baghoth et al., 2012; Shutova et al., 2014).

The average total THM concentration of the treated water was 88.8 µg L^{-1} (31.8 - 251 µg L^{-1}) (Figure 8).

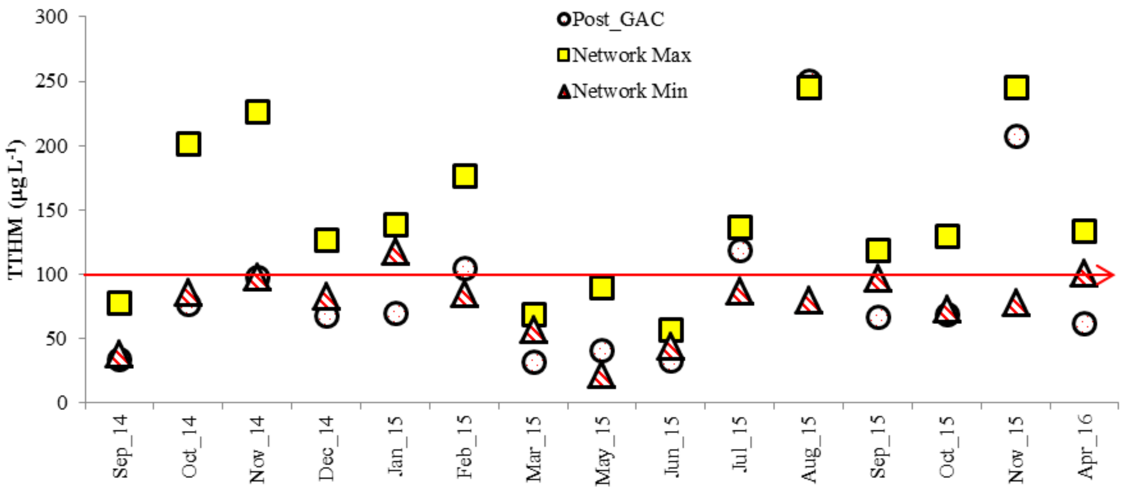

Figure 8. Total trihalomethane concentrations following treatment (Post_GAC) and at a number of locations in the network (Network Max and Min).

Chloroform was the most prominent THM (average ~72%) across all samples taken, followed by bromodichloromethane (~20%), dibromochloromethane (~6%) and bromoform (<1%). Average TTHMs across the distribution network displayed similar temporal changes as DOC with ambient temperature and episodic rainfall events. The average free chorine concentration was 1.07 mg L^{-1} however values of 0 mg L^{-1} were observed indicating that TTHM formation was chlorine limited at extremities in the network. The average DOC concentration measured from 9 locations along the distribution network was 5.59 mg L^{-1}. At DOC >4.0 mg L^{-1} it is likely that THM levels will exceed 100 µg L^{-1} if the residence time in the network is 2-3 days and if a free residual chlorine is to be maintained at the tap. Comp 2 had the highest fluorescence intensity in the distribution network followed by Comp 1 and Comp 3. THMs exceeded the parametric value of 100 µg L^{-1} on eleven out fifteen sampling occasions.

Significant correlations were highlighted among DOC, UVA_{254} SUVA, PARAFAC components Comp 1, Comp 2 and Comp 3, TN, chloroform (CHCl3), and total THMs. UVA_{254} and C1 had equal correlation scores (0.72) to DOC (Table 1). TN was significantly correlated with UVA_{254} and chloroform. C1, C2 and C3 were significantly correlated with UVA_{254} and chloroform. SUVA displayed a weaker correlation with chloroform than the PARAFAC components.

Table 1 Summary of Spearman's rank correlation coefficients between parameters.

	DOC	UVA_{254}	SUVA	Comp1	Comp2	Comp3	Comp4	TN	CHCl3	TTHMs
DOC	1	0.72*		0.72*	0.49*	0.67*				
UVA_{254}		1.00	0.62*	0.82*	0.56*	0.69*		0.52*	0.64*	0.61*
SUVA			1.00						0.48*	
Comp1				1.00	0.56*	0.77*			0.57*	0.56*
Comp2					1.00				0.53*	0.49*
Comp3						1.00			0.52*	
TN								1.00	0.62*	0.63*

Dissolved organic carbon (DOC) and total nitrogen (TN) are measured in mg L^{-1}. UVA_{254} and SUVA are measured in nm and L mg^{-1} m^{-1} respectively. Comp1, Comp2, Comp3 and Comp4 are represented as Fmax/ Raman Units and THMs are show in µg L^{-1}. * Correlations are significant (P<0.05).

ACKNOWLEDMENTS

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THE DINGLE TOE: STRATEGIC USE OF GROUNDWATER TO REDUCE WATER TREATMENT EFFORTS WHILE IMPROVING WELL INSTALLATIONS AT THE SAME TIME

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1. INTRODUCTION

A pilot project was initiated in May 2016 under the Source Protection Programme at Irish Water / Kerry County Council to investigate the potential of converting raw water sources from lake water to groundwater, under an exploration well drilling schedule in the Old Red Sandstones (ORS) at the Dingle toe. As described in previous papers today, it is expected any change to groundwater as the source, will require less treatment than surface water, as the lakes in Kerry are often impacted by peats/leaf matter. The advantage is that with groundwater as the source, the formation of disinfection by-products will be limited, in particular the Trihalomethanes (THMs).

Kerry Co Co. appointed a competent contractor experienced in construction of water wells (Munster Drilling) to drill 3 No. exploration/trial water wells at 3 No. Water Treatment Plants (WTP) to determine the yield capacity of such wells and carry out chemical and bacteriological sampling in Summer/Autumn 2016 on the Dingle Peninsula, Co. Kerry at the following locations:

- Tobar Brendain (Ballyferriter)
- Ceann Tra (Ventry)
- An Mhin Aird Puc (Annascaul)

Walkover surveys and desk study geological reviews incorporating the Dingle GWB (Groundwater Body) Report (GSI 2004), anticipated groundwater flow in fractures and faults concentrated in the upper 15 m of the aquifer, with deeper inflows from along fault zones or connected fractures. The GSI note significant yields can be obtained where boreholes are drilled into known fault zones. The location of the drilling sites is shown in Figure 1.

Additionally, the pilot, facilitated the implementation of the EPA Drinking Water Advice Note No. 14 (Borehole Construction and Wellhead Protection) and to recognise same in any future procurement of well works.

RPS Aquaterra, Dun Laoghaire, were appointed the Consultant Hydrogeologists tasked with carrying out the Irish Water Scope of Works to include the design of the boreholes and drilling hydrogeology supervision, and they reported to Paul Cremin, Capital Programme Regional Lead (South), Asset Delivery.

Figure 1. Location of the Drilling Sites

2. KERRY TRIAL WELL DRILLING PROGRAMME

The trial well locations were selected within existing water treatment sites under the ownership of Kerry County Council (KCC).

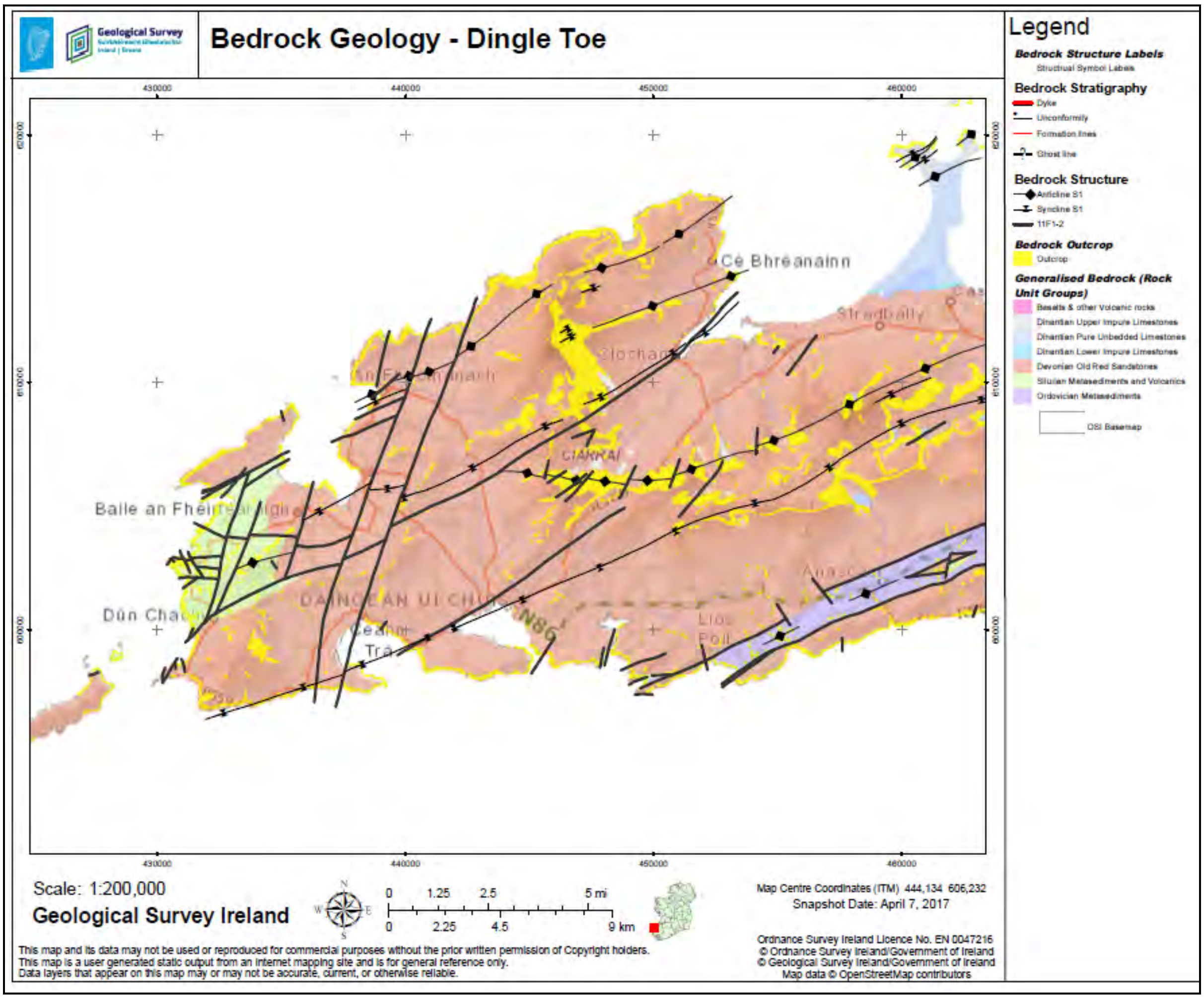
Munster Drilling Ltd commenced the drilling works on the 3rd of October 2016 and continued until the 11th of October under the full time supervision of an RPS hydrogeologist. RPS was appointed (Dr. Janka Nitsche, RPS Aquaterra) to ensure each well was completed satisfactorily in agreement with Irish Water's design specification, based on the Institute of Geologists of Ireland (IGI) Guidelines on Water Well Construction (2007), and EPA Note 14 (2013). The agreed maximum depth for each well was 120 metres using an air rotary drilling method, and if drilling conditions allowed each borehole would be completed as a production well.

All three borehole locations lie within the Devonian Old Red Sandstone, classed as Ll: Locally important aquifer, moderately productive only in local zones, as per Figure 2. Site records and drilling returns showed the following:

2.1 Tobar Brendain (Ballyferriter)

The topsoil at the Ballyferriter site is classed as predominantly shallow soils derived from noncalcareous rock or gravels with/without peaty surface horizon based on the Teagasc soil classification system. There is no listed subsoil beneath the site as bedrock is close to or at the surface. The geology consists of grey and red siltstones and mudstones of the Ballyferriter Formation, part of the Devonian Old Red Sandstones rock group, and the Brandon Head groundwater body (GWB). Rockhead at 2m.

Figure 2. Regional ORS Geology of the Study Area at Dingle Toe



2.2 Ceann Tra (Ventry)

The soils at the Ventry site consist of deep well drained mineral soils derived from mainly non-calcareous parent materials. The subsoil is comprised of sandstone till (TDSs), derived chiefly from Devonian sandstones. The geology at the site is comprised of purple sandstone and various siltstones of the Eask Sandstone Formation, which are part of the Devonian Old Red Sandstones. Dingle GWB. Rockhead at 22m. See borehole log in Appendix.

2.3 An Mhin Aird Puc (Annascaul)

The topsoils at the Annascaul site are described as predominantly shallow soils derived from non-calcareous rock or gravels with/without peaty surface horizon. There are no subsoils listed for the site location as the bedrock is at surface. The bedrock consists of bedded sandstone of the Ballymore Sandstone Formation, which is also a member of the Devonian Old Red Sandstones rock group. The Ballymore Formation represents part of an historic axial fluvial system. Dingle GWB. Rockhead at 17.5m.

2.4 Summary Drilling Results

Table 1 describes the drilling installations for all three locations, recording importantly the grouted depth and slotted interval for each borehole. As all three wells had once off funding, the wells were designed to be converted into production wells contemporaneously with the shallow steel casing grouted in place to exclude shallow groundwater inflows through subsoil and weathered rock. Nevertheless, pumping tests on each will determine the pump purchase and pump depths, and also to establish the sustainable drawdown of the water level in the borehole.

Table 1. Drilling Results Summary Table

Well Location	Total depth (mbgl)	Measured Yield (m^3/h)	8" Steel & Grouting depth (mbgl)	6" PVC Slotted Interval (mbgl)	Geology	Significant Water strikes (mbgl)
Tober Brendain	120	20.0	12	55-120	Grey & Red Siltstone	84, 85
Ceann Tra	96	40-50 (Estimate)	24	36-96	Siltstone & Sandstone	Multiple between 52-74
An Mhin Aird Puc	120	4.5	12	55-120	Green & Red Sandstone	17.5, 22.5, 31, 40, 61, 95

mbgl – metres below ground level

In the future, works to be procured in the Capital Investment Plan of 2017-2021, will undertake the normal sequence of exploration boreholes/trial wells, pump-tests, reporting, to be subsequently followed up with wider diameter production well drilling and commissioning pump tests. This will ensure agreement with the grouting requirements of EPA Advice Note No. 14, that any cement grout is injected into the annulus around the casing from the bottom of the casing up to the surface, and its pump installation requirements too, that any pump is positioned inside the pump chamber casing, above the inflows of water.

3. RAW WATER TREATMENT PLANTS AT DINGLE TOE

Table 2, summarises the existing water treatment plant design capacity, the current demand for the three sources, the current source type and the potential yield to be achieved with the three new groundwater sources/wells.

Table 2. New Well Yield and WTP Capacity

Plant Name	24 Hr Design Capacity (m3/day)	Current Demand (m3/day)	Current Source Type	New Well Yield Achieved (m3/d)
Tobar Brendain Water Treatment Plant	240	192	Surface water spring & two groundwater wells	480
Ceann Tra Water Treatment Plant	840	408	Surface water lake	1200
An Mhin Aird Puc Water Treatment Plant	720	408	Surface water lake	108

The estimated yields at Ceann Tra and Tobar Brendain significantly exceed the current demands and plant capacity at each. A new well supply at each will allow the reliance of the lake/surface water to be reduced which currently experiences water quality issues during heavy rainfalls and to realise the potential for ORS sourced groundwater, that it can provide a source of water that has a lower and more stable Natural Organic Matter (NOM) characteristic than surface water.

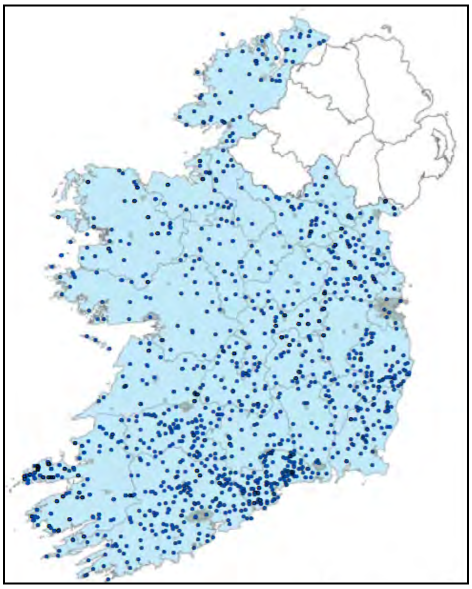
4. NATIONAL ASSET MANAGEMENT OF GROUNDWATER SUPPLIES FEEDING WTPs

Delivering a safe and reliable drinking water supply to over 80% of the population requires the abstraction, treatment and delivery of over 1,600 million litres of water each day. At present, we supply drinking water to 3.8 million people through 918 water treatment plants (WTPs). Due to the previously fragmented nature of the management of water services across the local authorities, the level and quality of data and records vary widely. Consequently, we have been carrying out asset surveys to increasing levels of detail, in order to achieve clarity on our raw water sources abstracted for drinking water purposes before treatment.

Of the national 918 count of WTPs, 534 are sourced from boreholes, and 148 are sourced from springs. In actuality 682 (74%) of our WTPs are fed by groundwater as the raw water source. There are also groundwater sources which are blended into larger surface water sources which are not presently classed as being groundwater, and overall nationally, there are linkages between groundwater and surface water which need more examination.

Irish Water are to apply an asset management approach to achieve the optimum capacity from our existing WTP infrastructure on a national basis. This requires the development of IT systems, including a new groundwater database and Geographical Information System, to collate and display the location, condition and performance of our numerous groundwater assets. These decision support systems will enable us to plan future maintenance and planned replacement of our groundwater assets at least cost, and to best practice.

Figure 3. The Density of National WTPs

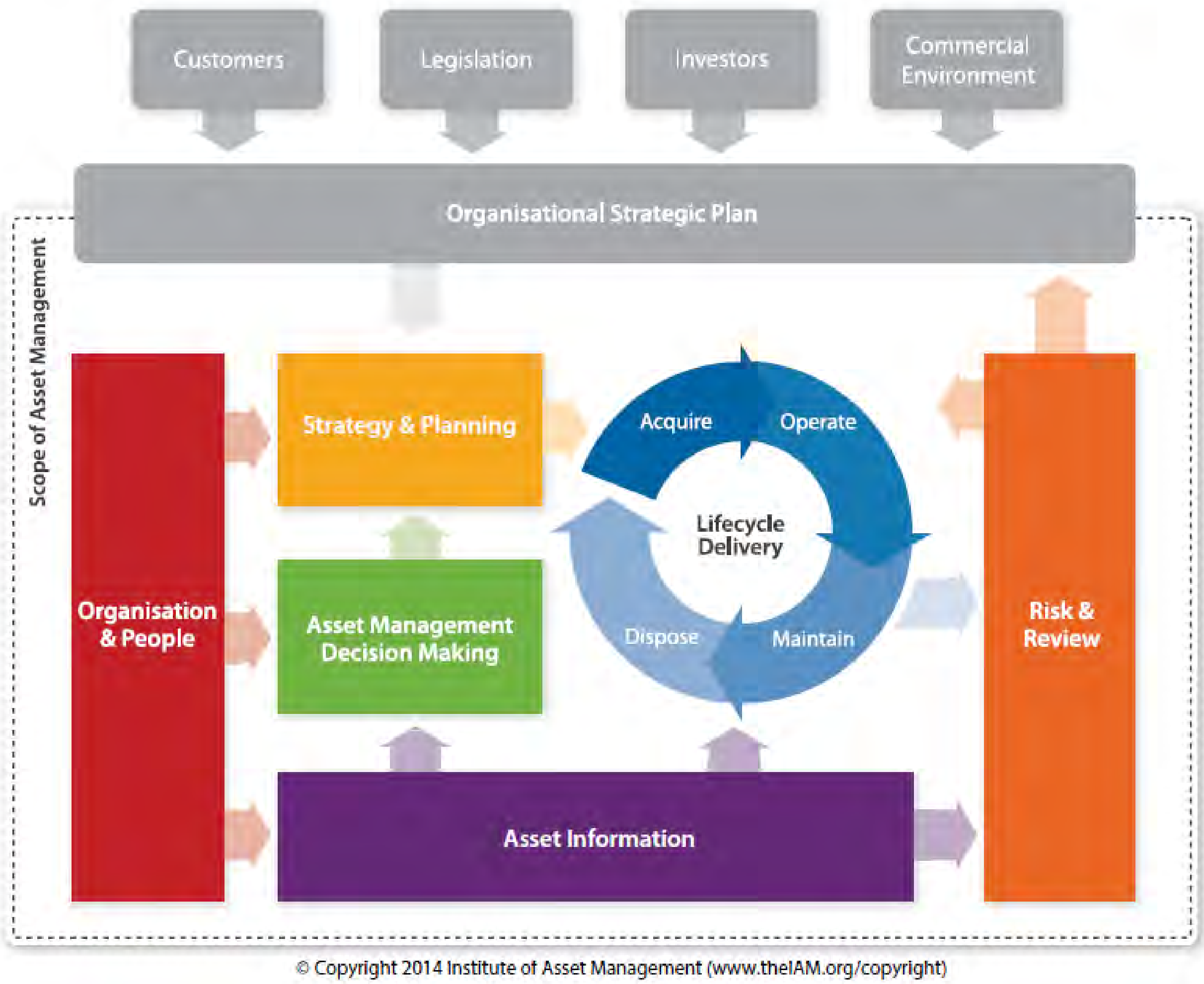


The management of our raw water assets as source of water will be delivered through the newly formed ‘Asset Planning’ section, alongside a new ‘Asset Intelligence’ section. We are defining our groundwater assets by the use of three approaches, to build a better picture of our groundwater network:

1. Groundwater Database
2. Risk assessment in accordance with the DWSP (Drinking Water Safety Plan) Process (EPA 2011)
3. Groundwater GIS layer on Asset Information architecture

We also intend to use best practice, the Institute of Asset Management (IAM), principle of ‘Lifecycle Delivery’ to manage assets from concept to disposal. Figure 4, identifies the life cycle stages used in the Lifecycle Delivery under the Asset Management Model which Irish Water aims to follow.

Figure 4. The Asset Management Model (Institute of Asset Management). See blue ‘Lifecycle Delivery Loop’



Within the Loop (see blue shading) it is intended to drive the ‘Maintain’ element on the groundwater assets, as our daily work, and summarised in Table 3. There will be three elements to our schedule:

i. Inspection, Monitoring;
ii. Preventative Maintenance; and,
iii. Corrective Maintenance.

We expect to engage on the three elements with consultancy support and the services of well drillers nationwide, to which we recently organised procurement on.

Table 3. The Three 'Maintain' Elements, we want to achieve at our 680+ Groundwater Assets (*after* Institute of Asset Management)

- **Inspection, testing & monitoring** – activities to confirm the safety and integrity of assets and to provide information for determining maintenance and renewal needs. This encompasses periodic visual inspections, sophisticated diagnostic testing and remote condition monitoring systems.
- **Preventative maintenance** - planned activities to prevent or reduce the impact of faults, failures or excessive deterioration. Preventative maintenance is based on risk, and related to the maintenance regime being applied to an asset (time-based, condition-based, usage/duty-based).
- **Corrective maintenance** - activities performed to repair defects, damage or address a shortfall in performance in order to restore the asset to a defined standard and keep it operational.

5. FUTURE PROCUREMENT IN THE GROUNDWATER AREA

By better understanding our groundwater asset portfolio, by rationalising the abstraction points regionally, and by restructuring the individual assets to be more secure and to pump more efficiently, we can help to meet the drinking water quality and capacity deliverables set for Asset Planning by the Irish Water Business Plan, and fulfil our objectives under the Water Services Strategic Plan (WSSP).

By using the 'Lifecycle Delivery' loop, it will enable us to plan the future of our water supply more efficiently.

Key to delivery will be the procurement of support, particularly for the period of the latest Investment Plan 2017-2021.

Our initial requirements were presented to market (drillers and groundwater professionals) at the Spencer Hotel on 17th November 2016, at a Prior Information Notice (PIN) forum, for suppliers or services in:

71351220-1	Geological consultancy services
71313000-5	Environmental engineering consultancy services
45262220-9	Water-well drilling

The PIN forum was facilitated by *Geoscience Ireland*. Irish Water received eleven responses back from the meeting, by the closing date of 15th December. We reviewed all comments in detail, and have taken on board many of the issues raised. The outcome of this process has resulted in Irish Water going to market (April 2017) with the following two tenders:

17/049
Multi - Supplier Framework for the Provision of Subject Matter Experts in Hydrogeology and Groundwater Investigations

16/244
A Multi - Supplier Framework for Groundwater Drilling, Pump Testing and Remediation Works Associated with Water Supply Boreholes

The 17/049 tender is to establish a Framework for Subject Matter Experts in Hydrogeology and Groundwater Investigations in respect of: ZOC (Zone of Contribution) Delineation, Desk Studies and Field Assistance; and, Groundwater Supply Detailed Design and Scoping of Works and Field Investigations. The framework will consist of appropriately qualified and experienced individual groundwater consultants, who will provide expert groundwater and hydrogeological services, primarily pursuant to Irish Water's obligations under the Water Services Strategic Plan (WSSP), the National Water Resources Plan (NWRP), and through the implementation of the Drinking Water Safety Plan (DWSP) approach to be adopted at each water supply, as required by the EPA. The hydrogeologist and/or groundwater engineer will provide expert specialist advice, site supervision, and prepare expert reports as required by Irish Water on the basis of on-site assessments, observing any ground investigations and testing, in combination with all available data, all on a day rate.

The 16/244 tender is to establish a Multi – Supplier Framework for Groundwater Drilling, Pump Testing and Remediation Works Associated with Water Supply Boreholes for the provision of appropriately qualified and experienced individual groundwater drilling contractors to provide expert groundwater drilling services. The drilling contractor will provide groundwater drilling, pump testing, and well rehabilitation works associated with water supply boreholes as required by Irish Water on the basis of ground investigations and testing.

6. CONCLUDING REMARKS

Currently Asset Planning as the Water Supply Strategy team (Angela Ryan, Malcolm Doak, and Aodhnait Ní Chathasaigh) are classifying 680 approx. groundwater assets to build a better picture of our groundwater network, and we regularly meet with our geoscience stakeholders, namely the Geological Survey, for which we express gratitude in the support they always give. Setting up the early days of a maintenance plan for each borehole or spring, initiating a DWSP for each, and planning for source protection ZOC studies, is a big part of our daily work.

The next years will be busy in managing individual engagements with the SME groundwater consultancy support framework and in directing the services of well drillers nationwide alongside with our colleagues in Asset Delivery.

Overall, it is fitting to speak at IAH under the Session: DOC & THM, since as we work on each groundwater asset, and particularly at the boreholes, by changing pumping regime to a more sustainable rate and with good stable drawdown control, the quality of groundwater clearly requires less intensive treatment than surface water, to make it safe to drink. Groundwater is a key share of the Irish Water drinking water supply.

ACKNOWLEDGEMENTS

The author wishes to thank the staff at Kerry County Council for making the proposals to assess the groundwater potential of the Dingle Toe. The works and determination of Aidan Falvey and Shane Moriarty, Water Services Capital Office, and of Seamus O'Mahony Operations must be recorded. Everything about the groundwater in Kerry happened because of Gerry Baker, and his appetite for work! He is great at producing production wells under the most troublesome of tendering rules and regulations. Many thanks to the IAH Ctte in having the determination to run such a big conference on the Changing Water Services Environment.

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GSI 2004. Dingle GWB. 1st Draft Dingle GWB Description –26 January 2004

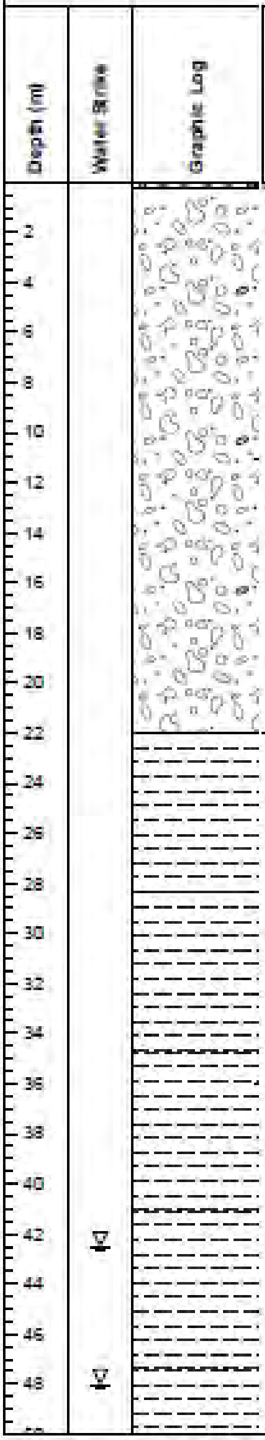
RPS (2017) Kerry Trial Well Drilling Programme - Drilling Report MDW0753Rp001. Janka Nitsche, Gerry Baker PGeo.

Borehole Log

PROJECT NUMBER DD2037B/I1	**DRILLING COMPANY** Munster Drilling	**DRILLING DATE** 05-06/10/2016
PROJECT NAME Dingle WS	**DRILLER** Mark Linehan	**COORDINATES**
CLIENT Irish Water	**DRILLING METHOD** Air Rotary	**COMPLETION** Concrete Plinth
LOCATION Ceann Tra	**HOLE DIAMETER** 10" to 24m; 8" to 96m	**SURFACE ELEVATION**
BOREHOLE NAME BH1	**TOTAL DEPTH** 96.0m	**ESTIMATED YIELD** 40m3/hr

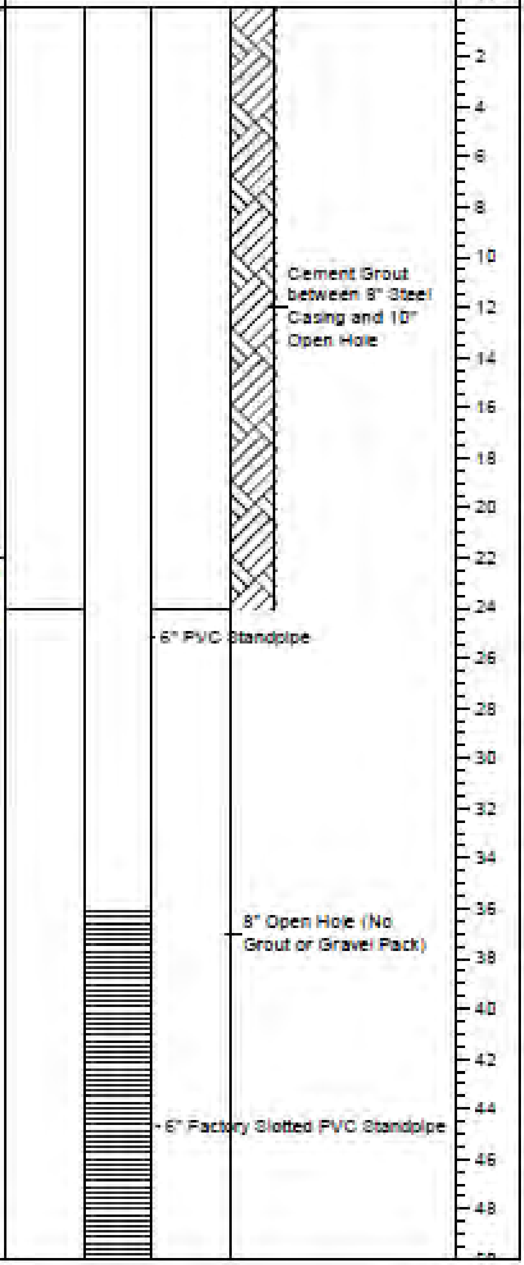
Casing 8" (Steel) to 24m; 6" (PVC) to 96m.

LOGGED BY Janka Nitsche
CHECKED BY Gerry Baker

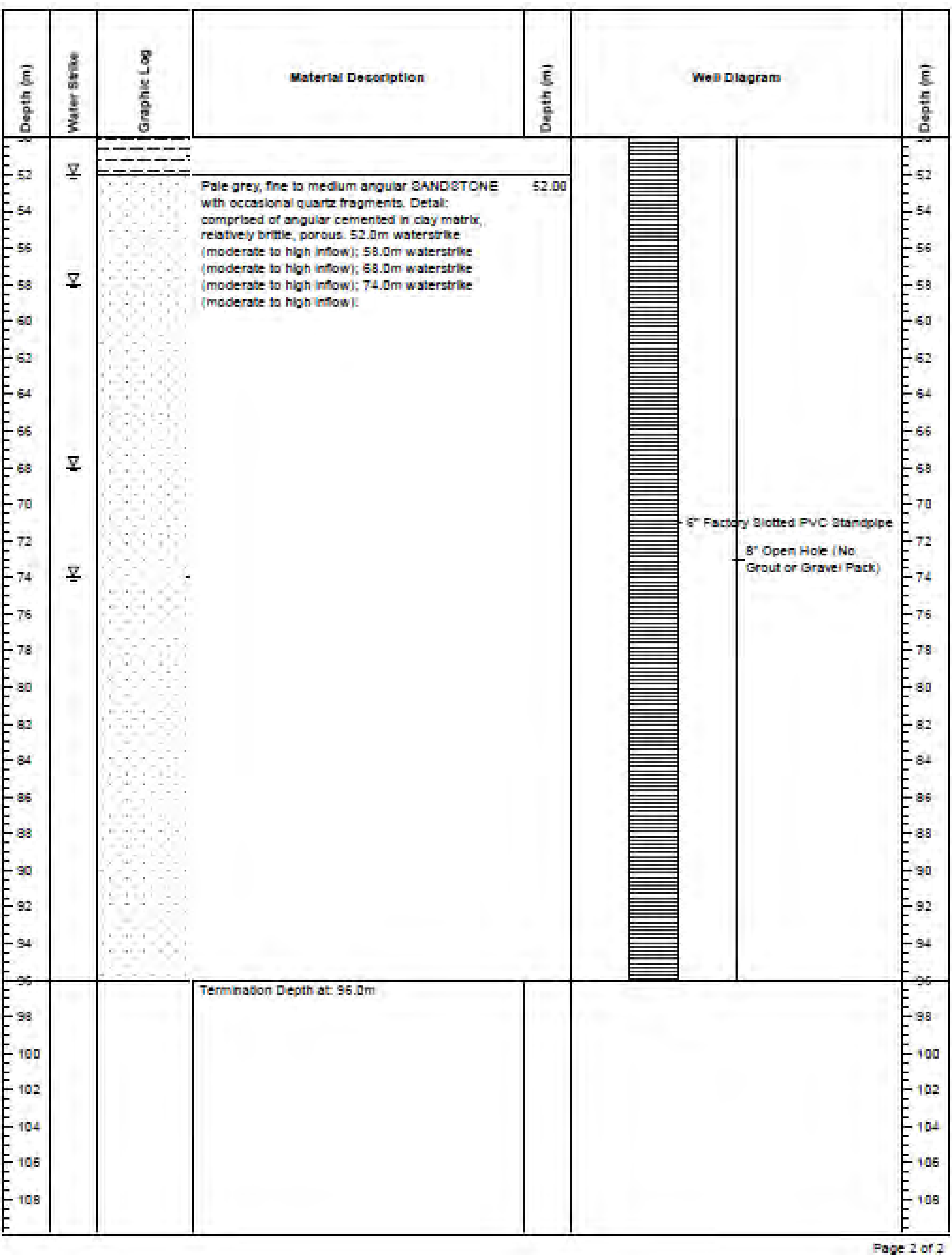


Material Description	Depth (m)
Gravel FILL (MADE GROUND)	0.20
Brown slightly clayey gravelly SAND. Gravel is tabular, angular to subrounded, fine to coarse. Occasional boulders. Detail; 0.2-2.0m damp, below 2.0m dry. 13.0m onwards; pale brown in colour.	
Weathered orange/red SILTSTONE. Power-like returns. Dry.	22.00
Various coloured SILTSTONE. Powder-like returns. Dry. Detail: 24.0-29.0m orange brown; 29.0-30.0m red brown; 30.0-32.0m dark brown; 32.0-33.0m red brown; 33.0-34.0m orange brown; 34.0-35.0m pale brown; 35.0- 38.0m pale pink brown; 38.0-52.0m medium to dark brown. 42.5m waterstrike (slight inflow); 48.0m waterstrike (slight inflow).	24.00

Well Diagram



Page 1 of 2


Depth (m)
Water Strike
Graphic Log
Material Description
Depth (m)
Well Diagram
Depth (m)
Pale grey, fine to medium angular SANDSTONE with occasional quartz fragments. Detail: comprised of angular cemented in clay matrix, relatively brittle, porous. 52.0m waterstrike (moderate to high inflow); 58.0m waterstrike (moderate to high inflow); 68.0m waterstrike (moderate to high inflow); 74.0m waterstrike (moderate to high inflow).
52.00
6" Factory Slotted PVC Standpipe
8" Open Hole (No Grout or Gravel Pack)
Termination Depth at: 96.0m
52
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GROUNDWATER DISSOLVED ORGANIC CARBON (DOC) AND HUMAN HEALTH RISKS: SOME ISSUES TO CONSIDER

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ABSTRACT

This paper presents a summary of a forthcoming invitational article which will be published in the 2017 Hydrogeology Journal Special Issue on "Hydrogeology and Human Health". The article examines the occurrence of dissolved organic carbon (DOC) in groundwater and the associated issues capable of indirectly affecting human health. DOC is a near ubiquitous component of natural groundwater with concentrations typically <4 mg C/l in natural/unpolluted sources. Concentrations above these levels generally signify some level of anthropogenic influence and/or contamination issues, thus reflecting potentially compromised water quality. However, DOC is a diverse and complex mixture of compounds, particularly with relation to the presence of humic components; accordingly, direct associations between DOC concentration and human health risk are difficult to quantify. Treatment processes used to ameliorate groundwater with high organic contents, particularly chlorination, can result in the formation of carcinogenic disinfectant by-products (DBPs), a recognised human health concern, however, to date, no examples or case-studies have been reported within the international literature. Similarly, the effects of elevated groundwater DOC on waterborne pathogens and other colloidal contaminants remains poorly understood. Recent years have witnessed major advances in the use of molecular laboratory techniques, and particularly polymerase chain reaction (PCR), invaluable tools for expanding our knowledge and understanding of subsurface microbial transport mechanisms and community dynamics. However, these techniques are also affected by naturally and anthropogenically elevated levels of groundwater DOC via inhibition, thus potentially resulting in false-positive laboratory results.

INTRODUCTION

Dissolved organic carbon (DOC) represents the carbonic fraction of dissolved organic matter (DOM), typically accounting for >90% of the total organic carbon (TOC) budget found in natural groundwaters (Batiot et al. 2003a). Numerous studies have examined the occurrence, source, reactivity, and transport of natural DOC in aquifers (Baker 2000; Chapelle et al. 2009; Longnecker and Kujawinski 2011; Shen et al. 2015); however, to date, few have focused on the indirect associations between DOC and human health. This is in part due to the diverse nature of organic compounds frequently encountered in both polluted and unpolluted groundwater, in addition to their variable levels of reactivity.

Organic matter (OM) of biological origin is the most frequently oxidised substance in the aqueous environment and, due to the reactive nature of a subset of biomolecular components (Aiken 2002), particularly humic substances, groundwater DOC is indicative and/or causative with respect to a number of subsurface microbial and geochemical processes. Some of these processes are considered beneficial, e.g. denitrification (Clay et al. 1996; Pabich et al. 2001; Thayalakumaran et al. 2008); however, DOC enrichment directly affects microbial oxygen availability and, thus, subsurface microbial survival and mobility (Aravenaa et al. 1995; Chapelle et al. 2009; Thayalakumaran et al.

2015). Moreover, high levels of dissolved organic matter (DOM) present in groundwater may decrease optical clarity (or increase turbidity), which can significantly reduce the efficacy of specific treatment processes (e.g. UV disinfection) and complications can arise with the formation of DOC by-products following chemical disinfection.

TOC IN GROUNDWATER

Shallow groundwater DOC characteristics are largely determined by processes operating in the soil organic horizon (Trumbore et al. 1992; Kalbitz et al. 2000), while the transfer of organic matter remaining in solution is primarily dependent on vadose zone thickness (Pabich et al. 2001; Batiot et al. 2003b; Goñi and Gardner 2003), and the level of hydraulic connectivity between subsoil horizons and the watertable (Kalbitz et al. 2000). Thus, the hydrological connectivity between the surface and subsurface is important for the transfer of DOC into shallow groundwater ecosystems, which will also be influenced by soil properties/structure and land management practice. Whilst elevated groundwater DOC (>4 mg C/l) can occur naturally due to recharge being influenced by discharge originating from wetland environments and the presence of sedimentary organic deposits, high DOC is often associated with anthropogenic activities (Chomycia et al. 2008), such as leachate from waste disposal, irrigation and fertilisation.

TOC AND HUMAN HEALTH

The composition and bioavailability of DOM are key factors affecting water quality, where observed increases in DOC concentration may be indicative of changes in water quality. Whilst there are a number of issues that may be associated with TOC in groundwater and human health, such as metal mobility (Christensen et al. 1999), the following sections provide a brief overview of some frequently overlooked issues capable of indirectly affecting human health.

DOM Treatment

High levels of DOM in water are known to cause aesthetic and odour problems, while possibly promoting the growth and proliferation of pathogenic bacteria (Pernthaler 2005; Goldscheider et al. 2006; Gopal et al. 2007). The solubilization of heavy metals by complexation with humic substances is known to be of considerable importance in coloured natural waters (Oliver et al. 1983), whilst the persistence of high DOC loading has significant implications for the fate of other contaminants such as pesticides, pathogens, and pharmaceuticals, as hypoxic conditions may restrict the degradation of many carbon-based compounds (Chomycia et al. 2008).

Treatment processes for DOM is typically followed by disinfection via chlorination in order to ensure satisfactory potable water supplies and to prevent microbial growth during distribution (Chomycia et al. 2008; Uyak et al. 2008) and has been shown to effectively reduce DOC concentrations (Drewes and Jekel 1998; Westerhoff and Pinney 2000; Kim and Yu 2007). However, humic substances are difficult to remove from solution and react with chlorine in the disinfection process to produce disinfection by-products (DBPs), most notably trihalomethanes (THMs), many of which are suspected carcinogens (WHO, 2011).

Whilst connections between human cancer occurrences and ingestion have been made for treated surface-water supplies, there are no such studies from supplies using publicly supplied groundwater. With significant proportions of domestic and public drinking water wells located in close proximity to agricultural activities that require treatment, this may be a significant and persistent, yet poorly understood, health risk, both in developing and developed countries. Moreover, the use of reclaimed and treated wastewater for engineered aquifer recharge is an increasingly common practice in many regions of the world, such as China, which suggests that aquifers utilised by human populations, both in urban and rural areas, may already be characterised by undesirable DBP concentrations.

Organic matter and colloidal mobility

“Colloidal contaminants” include some of the earliest known pollutants recognised to impact water quality such as pathogenic microorganisms (bacteria, viruses and protozoa; Macler and Merkle 2000). More recent investigations have recognised that natural colloidal materials can facilitate the transport of low solubility substances (Kretzschmar et al. 1999), while, by-products of recent technological developments, including engineered nanoparticles (Nuttall and Kale 1994), represent emerging contaminants of concern that may also impact human health (Troester et al. 2016). In contrast to solutes, pathogens can cause infection at extremely low levels of exposure and are often associated with rapid (<10 year) subsurface flow (Hunt and Johnson 2016).

However, despite recent progress in characterising colloid-OM interactions in the laboratory (Yang et al, 2010), DOC’s influence on colloid migration in groundwater systems remains largely uncharacterised. Nonetheless, results from laboratory analysis on the influence of OM on colloid mobility demonstrate how changes in ionic strength and pH alter the capacity of a well characterised humic acid to influence the colloid attenuation capacity of a saturated sand (Yang et al, 2010). Realistic conceptual models may therefore provide a reliable basis for upscaling and identification of potentially relevant settings, such as karst, where hydro-chemical changes have been demonstrated to effectively mobilise particles deposited under conditions more conducive to detachment (Flynn and Sinreich 2010). Similarly, as studies employing DOC have demonstrated, contrasts in concentration, which occur between the margins of a contaminant plume and its centre may give rise to contrasting colloid attenuation capacities (Harvey et al. 2011). Accordingly, it is suggested that some DOC may be capable of promoting or inhibiting colloid mobility at different stages of a plume’s development (Flynn et al, 2012). Furthermore, alterations to the content/configuration of deposited OM, arising from processes including OM degradation and/or changes in hydrochemistry, may give rise to temporal changes in the capacity of aquifers to disinfect groundwater.

The capacity to quantify those processes which control the interactions between OM and colloidal contaminants provides a means to more confidently investigate the behaviour of OM in saturated porous media and for colloidal contaminant transport in aquifers. Further development of this topic, necessary to protect groundwater supplies (Flynn et al, 2015), will require investigation spanning a range of scales and disciplines. Although there remains a need for further laboratory-based studies to identify and where possible quantify fundamental processes, a need for further field-scale investigations is critical if the importance of these processes in natural systems is to be appropriately defined. The role of the hydrogeologist is anticipated to prove fundamental in bridging this divide.

Inhibition of polymerase chain reaction (PCR)

Polymerase chain reaction (PCR) is increasingly being employed as the standard method for detection and characterization of (pathogenic and non-pathogenic) microorganisms and genetic markers in a variety of aquatic media including groundwater (Schrader et al. 2012). PCR has become a rapid, highly specific, low cost method for microbial detection, and is now regularly used in the fields of environmental science, hydrology, and hydrogeology (Abbaszadegan et al. 1999; Schrader et al. 2012). Moreover, due to increasing accuracy and specificity, in parallel with decreasing costs, these techniques are now frequently employed for quantitative risk assessment and regulation of both drinking and recreational waters (Gibson et al. 2012).

However, whilst this technique has been successfully employed to identify the source of disease outbreaks from contaminated groundwater supplies (e.g. Sezen et al. 2014), PCR inhibition by humic substances is capable of resulting in significant under-estimation or false-positive results (Abbaszadegan et al. 1999; Radstrom et al. 2008; Schrader et al. 2012), thus potentially resulting in a failure to correctly detect the source of an ongoing human health event associated with groundwater supplies. Groundwater derived from specific settings may be expected to comprise high levels of humic PCR inhibitors due to high groundwater DOC concentrations, i.e. karstic areas and peatlands

(Borchardt et al. 2003; Kolka et al. 2008), and should therefore be systematically analysed for inhibition prior to the use of PCR.

CONCLUSION

This paper identifies three key human health related issues associated with DOC in groundwater, namely the presence of DBPs, potential effects on colloidal transport mechanisms and inhibition of PCR techniques, in treated and/or untreated groundwater used in treated and untreated groundwater supplies water supplies. Future research efforts seeking to explore these issues should be directed with respect to groundwater DOC and human health, as currently, these topics are under-represented in the published literature.

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TECHNICAL WORKSHOP

TELEMETRIC DATA TRANSMISSION

Kenneth Freehill and William Delaney (Office of Public Works) and Rebecca Quinn (Environmental Protection Agency)

ABSTRACT

The OPW operates a surface water hydrometric network across Ireland to record river and lake water levels and to estimate river flows, with a focus on flood levels and high flows. The EPA (in conjunction with local authorities) operates groundwater and surface water hydrometric networks across Ireland to record river, lake and groundwater levels and to estimate river flows, with a particular focus on drought levels and low flows. In recent years the OPW and the EPA have telemeterised their networks and have implemented differing telemetry solutions based on the constraints and data requirements germane to each organisation. The OPW in their flood management role, have an operational requirement for real time data in order to support effective emergency response during flood events. The EPA mainly requires data for licencing and regulatory purposes and therefore only has a periodic requirement for real time data at some stations, typically to support the work of the OPW during flood events. The workshop presentations will focus on describing the various constraints and requirements faced by the OPW and EPA, how solutions were arrived at to address these issues in terms of equipment specification, power supply, transmission requirements etc. and the lessons learned during the process.

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